B. Ida Grove

B.1 Statement of Problem

The city of Ida Grove is located in central Ida County east and south of the confluence of Odebolt Creek with the Maple River (Figure B-1). The part of Ida Grove modeled for this report lies on the floodplain between the two streams. From the ground surface to 5 - 20 ft in depth is a surficial clayey deposit which is underlain by a shallow alluvial sand and gravel aquifer. There also exists a deep alluvial aquifer of about 50 ft thickness that is separated from the shallow aquifer by a 45-50 ft thick clay layer. The deeper aquifer is not included in this model since it has no evident hydraulic influence on the shallow aquifer and the main concern is groundwater contamination by the LUSTs in the shallow aquifer.

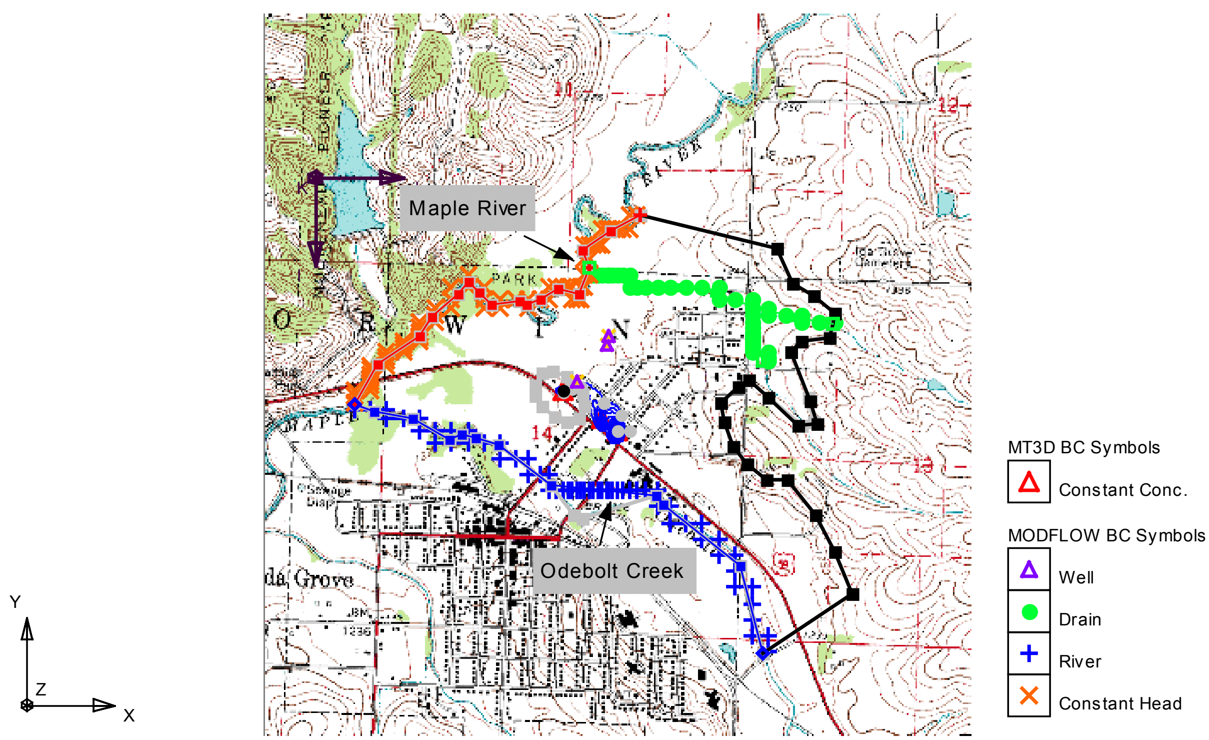


Figure B-1 The simulation domain with wells and sources

The city gets its water from four wells located on the floodplain in and near a petroleum contaminated zone. Two of the wells (#1 & #2) both produce at a rate of 120 gpm (654 m^3/d) from the more productive shallow aquifer. These wells pump on average for about 11 hours per day. Two other wells (#5 & #6) produce from the less productive deep aquifer. A fifth well (#3), which produces continuously from the shallower aquifer at a rate of 150 gpm (818 m^3/d), has been taken off production for the water supply, but is still pumped to provide hydraulic control of the petroleum plume and to protect the two shallow wells.

There are several LUST sites along US Hwys 59 & 175, and a petroleum contaminated zone extends northwestward for about 1000 ft from the farthest LUST site to well #3 (Figure B-1). Traces of the petroleum contaminant MTBE were found in wells #1 and #2 in samples from March of 1998 and March of 1999, but have not recurred. The petroleum contamination sources have affected the shallow sand and gravel aquifer.

B.2 Objectives

The purpose of modeling groundwater and contaminant transport at Ida Grove was to determine:

1) what the groundwater flow system is in the vicinity of LUST sites and city water wells;
2) whether city wells 1 and 2 are at risk of drawing the contaminant plume; and
3) whether contamination at LUST site 8LTZ58 threatens city well #3.

B.3 Hydrogeologic Characterization

Maps, borehole logs, water level data, other hydrogeological information, and groundwater contaminant concentrations for Ida Grove are taken from the IDNR LUST files

#8LTK99, 8LTA75, 8LTY18, 9LTE96, 8LTZ58, and 7LTB86. Additionally, a report presenting results of a pump test of well #3 (GeoTek, 1995) and a two-dimensional groundwater flow and contaminant transport model (Davis, 1995) were consulted. Another report presenting results of a pump test of the shallow aquifer at a prospective water well site one mile northeast of the current well field was also consulted (Kuehl and Payer, 2000).

According to the Geological Survey Bureau of IDNR, Ida Grove is at a geomorphic boundary between the Northwest Iowa Plains (north of the Maple River), and the Southern Iowa Drift Plain (south and east of the city). Pleistocene Age Pre-Illinoian tills underlie the surface west and north of the Maple River, but Wisconsinan tills (Sheldon Creek Fm.) underlie the surface to the east and south. Loess mantles all of the till terrain. In the river valley, this stratigraphy is complicated by Holocene Age erosional processes and alluvial deposition in the floodplain and terraces. (Jean Prior, written communication, June, 2001). Interbedded sandstones and shales of the Cretaceous Age Dakota Formation underlie the Pleistocene units. Well control is sparse in the region, and the positions of stratigraphic transition from floodplain to terrace to Pleistocene Age deposits are poorly known.

Groundwater in the shallow aquifer in the model domain is recharged by infiltration from rainfall and snowmelt throughout the area and generally flows westward from higher elevation towards the Maple River. Annual recharge to the water table is not precisely known, but is likely in the range of 2 to 6 inches (0.051 – 0.152 m/y) or 7 – 25 % of annual precipitaion. The depth to the water table ranges between about 7 and 17 ft (about 2 m to 5 m). Hydraulic conductivity is estimated to range between 90 - 152 m/d from the GeoTek (1995) tests, and between 106 - 136 m/d from the Kuehl and payer (2000) tests. The range is due in part to a 30 ft uncertainty in aquifer thickness. Storage coefficient was estimated to range between 0.003 -

0.005 from the former tests, and between 0.0002 - 0.002 from the latter tests. Heterogeneity in the shallower aquifer is vaguely indicated on drillers logs for the city well field ("sand-fine to very coarse; coarse to very coarse with boulders." Julie Sievers, written communication) and for the test wells (interbedded sand, clay, and gravel). Deep monitor wells drilled by GeoTek (1996) along the petroleum plume in Ida Grove also indicate minor, interbedded or lenticular, fine sand and clay heterogeneities in the shallower aquifer, but overall, the unit consistently seems to be coarse grained between depths of about 25 ft and 70 ft.

B.4 Groundwater Flow Modeling

B.4.1 Conceptualization and Design

The simulation domain shown in Figure B-1 is bounded by the Maple River to the northwest and by Odebolt Creek to the southwest. The Maple River is modeled as a constant-head boundary (the red crosses in Figure B-1) assumed to be well-connected with the shallow sandy and gravel aquifer. The river flows from northeast to southwest and its stage at the entering and exit points of the domain are 367.6 m and 366.7 m, respectively. Odebolt Creek is modeled with the river package in MODFLOW (the blue pluses in Figure B-1) to allow for losing and gaining conditions in the flow simulation. The creek has the highest water level of 371.8 m at the east and the lowest of 366.6 when it joins the Maple River. Its water depth plus its bed thickness is estimated as 1.0 m. The conductance of the creek bed per unit length is set at 1.0 m/day. The other boundaries of the domain are all treated as no-flow boundaries: the east portion is interpreted to be the interface between the shallow sand and gravel aquifer and the low permeability till, and the north portion as well as the southeast portion are flowlines.

A three-dimensional, two-layer model of Ida Grove was constructed to examine hydraulic behavior and contaminant transport in the shallow aquifer. The first layer represents the upper portion of the shallow sand and gravel aquifer with a hydraulic conductivity value of 25 m/day. There is a small low-permeable clay zone south of Well 3 within the first layer and the estimated K of that zone is 0.05 m/day. The lower layer is more permeable with K estimated to be 75 m/day. The depth to the groundwater table is usually 3 m and the thickness of the first layer is about 5 m and that of the second layer is 50 m. The conceptual hydrostratigraphy of the domain is shown in Figure B-2. The simulation domain is divided into an irregular grid which is refined at the three wells (Table B-1). The active cells consist of 46 rows, 45 columns, and 2 layers and are shown in Figure B-3.

Table B-1. Parameters for grid refinement at the three well

Well #	**Refine grid in X direction**			**Refine grid in Y direction**		
	Base cell size	**Bias**	**Max cell size**	**Base cell size**	**Base**	**Max cell size**
1	15	1.2	75	15	1.2	75
2	15	1.2	75	15	1.2	75
3	15	1.2	75	15	1.2	75

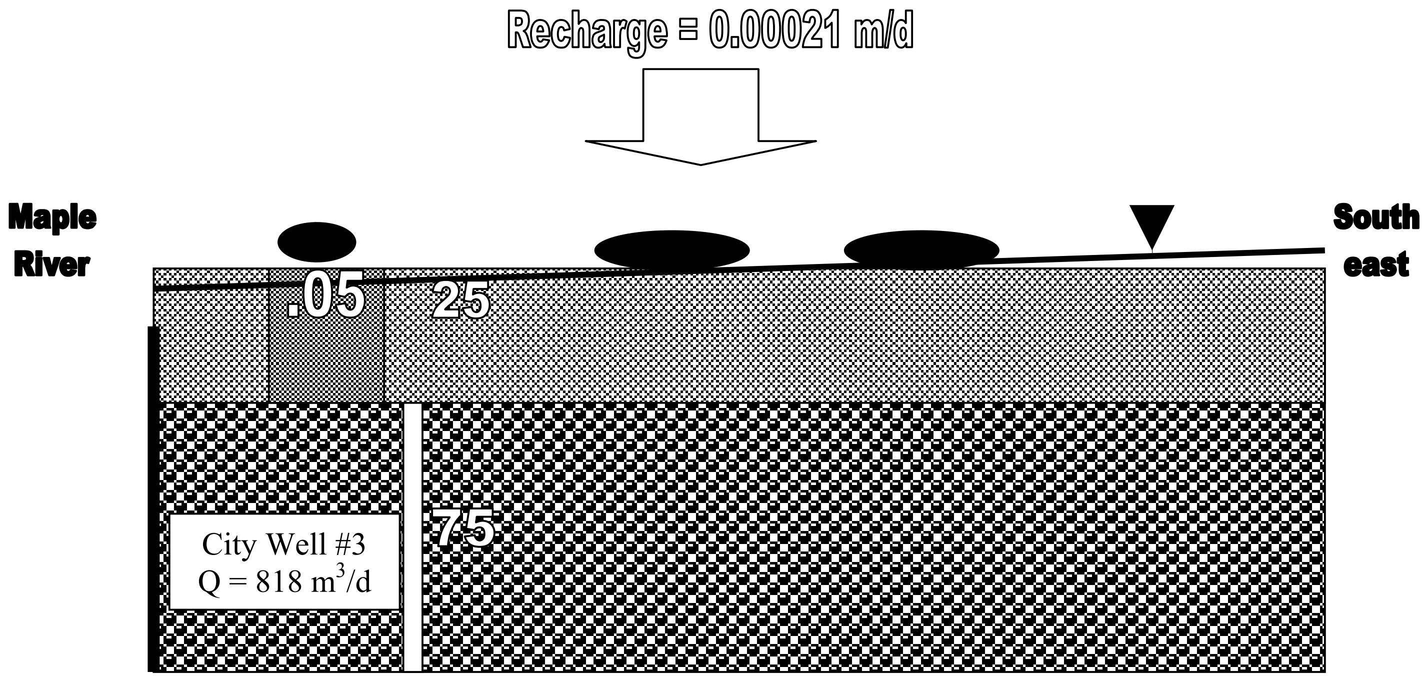


Figure B-2. Schematic NW-SE cross section of the Ida Grove conceptual model. Not to scale. Black triangle denotes water table; black ovals denote petroleum sources. Numbers within various fields are hydraulic conductivity (m/d) for the unit indicated.

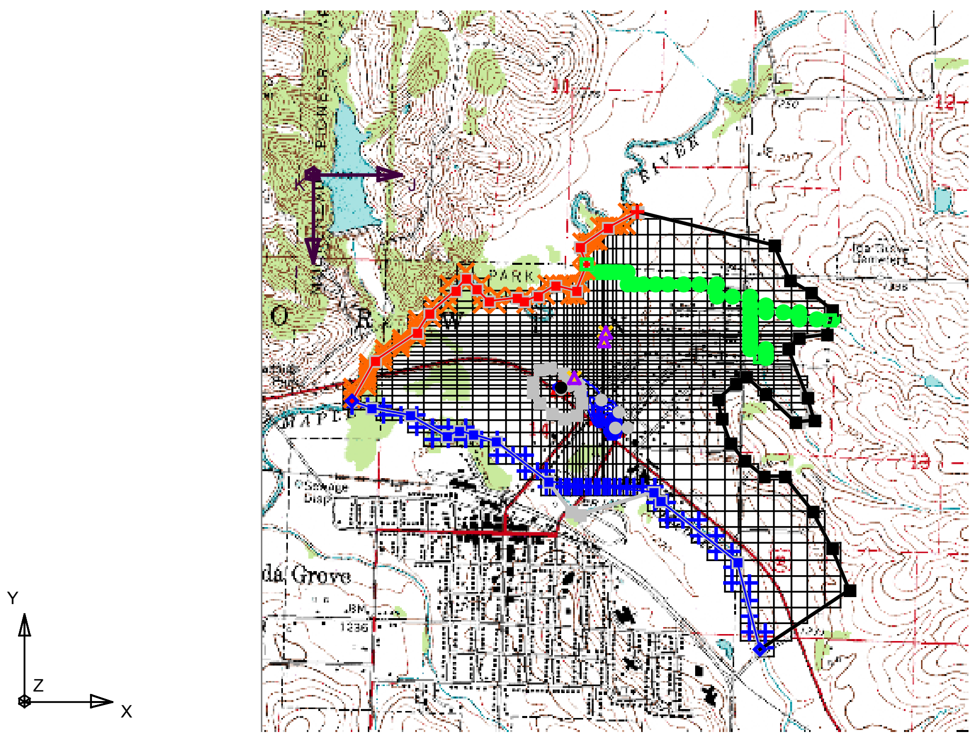


Figure B-3 Finite difference grids of the modeling domain at Ida Grove

B.4.2 Input Parameters

Four coverages for the model domain, Source/Sink, Layer 1, Layer 2, and Recharge, were created in GMS. The packages used in MODFLOW are: Basic, BCF, Well, Drain, Recharge, PCG2, and Output Control. The input parameter values for the Source/Sink coverage are listed in Table B-2 and B-3. Table B-3 also provides the locations and pumping rates for the three wells.

Table B-2. Input parameters for the river and creeks.

	Maple River	**Odebolt Creek**	**Unnamed Creek**
Simulated in MODFLOW by	Constant head	River package	Drain package
River stage *(m)*	366.7 – 367.6	366.7 – 371.8	N/A
River or drain bottom elevation *(m)*	N/A	365.7 – 370.8	367.3 – 387.1
River or drain conductance (m/day)	N/A	1.0	1.0

Table B-3 Pumping well locations and rates

Well #	**X** *(m)*	**Y** *(m)*	**I**	**J**	**K**	**Pumping Rate** *(m^3/day)*
1	296708	4691732	14	28	2	-654
2	296908	4691690	17	27	2	-654
3	296964	4691523	26	20	2	-818

The upper portion of the shallow sand and gravel aquifer is simulated with the coverage Layer 1. This layer is treated as an unconfined aquifer with bottom elevation at 364.23 m. It consists of two polygons or Zone I and II: the small low-permeable zone near well 3 is represented by Zone II and the rest of the layer 1 is Zone I. The main portion of the shallow aquifer is simulated as coverage Layer 2. This layer is treated as a confined aquifer of uniform thickness, with bottom elevation 350.5 m. Elevation input, horizontal and vertical hydraulic conductivities, and the net recharge rate are given in Table B-4. These values are estimated based on available data. Hydraulic conductivity is assumed to be isotropic ($K_h = K_v$).

Table B-4 Input parameters the layers for groundwater flow modeling

	Layer 1		**Layer 2**
	Zone I	**Zone II**	
Aquifer Type	Unconfined	Unconfined	Confined
Top Elevation *(m)*	400	400	N/A
Bottom Elevation *(m)*	364.23	364.23	350.5
Horizontal Conductivity, K_h *(m/day)*	25	0.05	75
Vertical Conductivity, K_v *(m/day)*	25	0.05	75
Net Recharge Rate, *(m/day)*	0.00021	0.00021	N/A

B.4.3 Model Calibration

The flow model is calibrated against the long-term average of the observed hydraulic heads at seven monitoring wells by changing the hydraulic conductivity, the net recharge rate, and the conductance of the two creeks. The calibration target is set to be within 0.5 m of the observed water levels and the results are listed in Table B-5. The calibrated conductance values are listed in Table B-2, the calibrated hydraulic conductivity values are listed in Table B-4, and the calibrated net recharge rate is 0.00021 m/day (3 in/yr). The calibrated steady-state head contours are illustrated in Figure B-4 along with a scatter plot of the observed vs. modeled head at the four monitoring wells and the error summary.

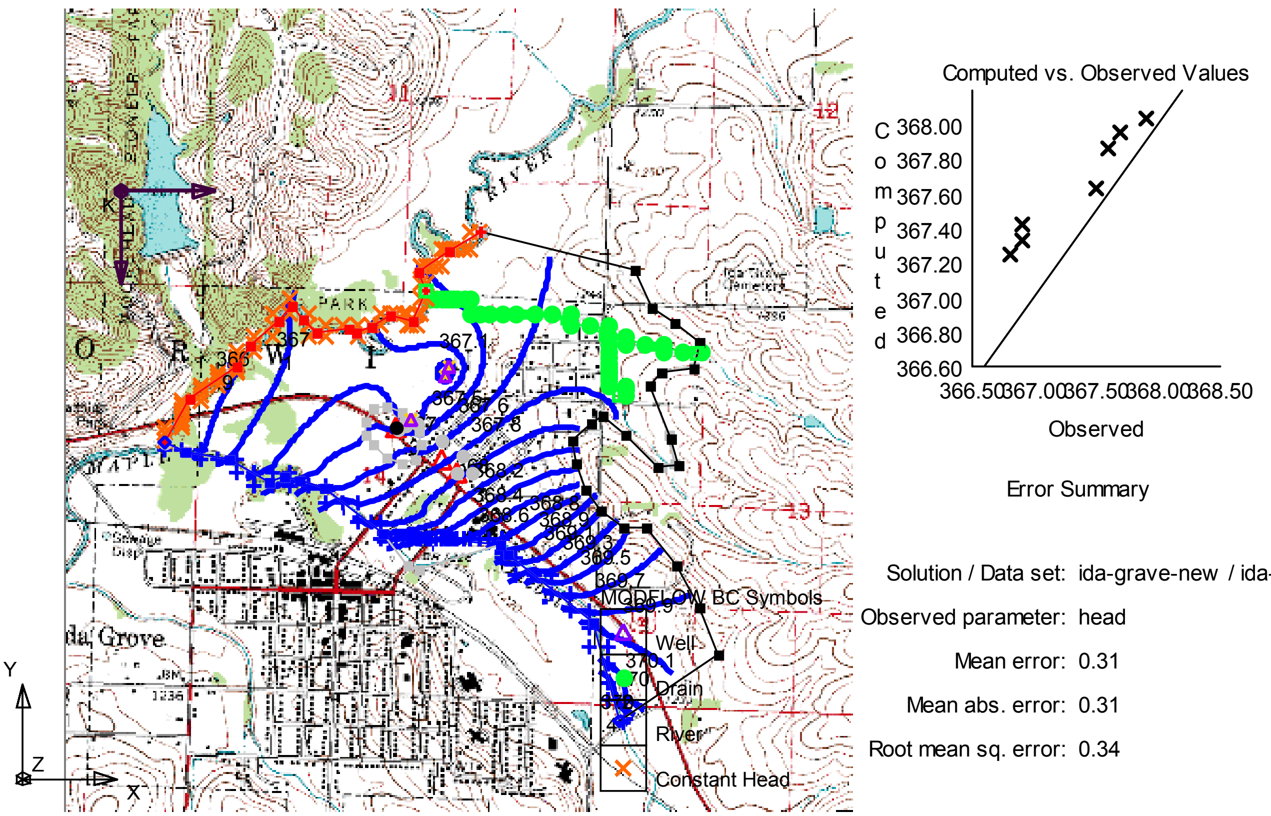


Figure B-4 Steady-state hydraulic head contours with calibration results.

Table B-5 Calibration results for hydraulic heads at observation wells

Well #	X *(m)*	Y *(m)*	I	J	K	Observed head *(m)*	Simulated head *(m)*	Error *(m)*
CMW-4	296742	4691492	28	19	1	366.90	367.32	0.42
CMW-16	296782	4691499	27	21	1	366.80	367.24	0.44
CMW-19	296708	4691479	28	17	1	366.90	367.42	0.52
RW-2	297004	4691304	33	32	1	367.90	368.03	0.13
RW-6	296947	4691307	33	30	1	367.70	367.95	0.25
RW-9	296966	4691372	32	31	1	367.60	367.85	0.25
RW-11	296881	4691429	30	26	1	367.50	367.62	0.12
Root Mean Square Error = 0.34								

B.4.4 Sensitivity Analysis

Two sensitivity simulations were carried out: one by doubling the values of hydraulic conductivity of Layer 1 and 2 and another by doubling the recharge rate in Table B-4. The simulation results are given in Table B-6. It is seen that the hydraulic heads are not sensitive to these changes. The RMSE increased slighty from 0.37 to 0.40 and 0.42, respectively. This is due to the fact that groundwater flow in this area is mainly controlled by the Maple River and Odebolt Creek.

Table B-6 Calibration results for hydraulic heads at observation wells with either K or the net recharge rate doubled

Well #	**X** ***(m)***	**Y** ***(m)***	**I**	**J**	**K**	**Error with K doubled** ***(m)***	**Error with recharge doubled** ***(m)***
CMW-4	296742	4691492	28	19	1	0.56	0.53
CMW-16	296782	4691499	27	21	1	0.60	0.50
CMW-19	296708	4691479	28	17	1	0.60	0.64
RW-2	297004	4691304	33	32	1	0.02	0.21
RW-6	296947	4691307	33	30	1	0.16	0.32
RW-9	296966	4691372	32	31	1	0.20	0.32
RW-11	296881	4691429	30	26	1	0.14	0.19
Root Mean Square Error =						0.40	0.42

B.5 Contaminant Transport Modeling

Five LUST sites are mapped along the highway, including one (8LTZ58) that is perched on a low permeability clay layer. An extensive monitor well network exists between the LUST sites and city water well #3 but monitor well control close around water wells #1 and #2 is lacking. Three contaminant sources corresponding to highest reported benzene concentrations at the LUST sites, 8LTZ58, 8LTA75, and 7LTB86 were simulated in the transport model. The modeled contaminant is benzene from the three LUST sites. The benzene plumes are simulated with MT3D in GMS v. 3.1 based on the steady-state groundwater flow condition obtained in Section B.4.

B.5.1 Model Conceptualization and Design

The simulation domain is the same shown in Figure B-1 with no solute flux across all the boundaries. The three LUST sites are treated as internal constant concentration sources and their location and concentrations are given in Table B-7. The times and amounts of petroleum released from the sources are uncertain. Source concentrations used are the maximum benzene concentrations in groundwater reported from monitor well samples at the individual sites.

Table B-7 Source locations and concentrations at the three LUSTs

LUST #	**X** ***(m)***	**Y** ***(m)***	**I**	**J**	**K**	**Benzene Concentration** ***(ppb)***
8LTZ58	296704	4691487	28	17	1	30,000
8LTA75	296878	4691356	32	26	1	12,000
7LTB86	296945	4691307	33	30	1	25,000

B.5.2 Input Parameters

Four packages, Basic, Advection, Dispersion, and Chemical Reactions, are used in MT3D. Some of the parameters in the Basic package is listed in Table B-8. The method of characteristics (MOC) is selected in the Advection package.

Table B-8 Stress period and time step information in Basic package of MT3DMS

Stress period	**Stress period length *(day)***	**Max transport steps**	**Initial time step size**	**Time step bias**	**Max time step size**
1	3650	20000	365	1	365

The other parameters needed in this simulation are effective porosity (n_e), dispersivity (α), and biodegradation rate (λ). Adsorption is neglected in the coarse grained aquifer. These parameters have not been determined from aquifer samples, so assumptions were made based on experience and on the borehole log descriptions, which show dominancey of coarse, sandy material. The value for effective porosity is estimated to be 0.2. The value for longitudinal dispersivity (α_x) is estimated by noting the minimum plume length (between 8LTA75 and well #3) is about 600 ft, so the estimation formula of Neuman (1990) yields a value of 65 ft (20 m). However, the value of 15 m is used for α_x because part of large-scale heterogeneity (i.e., layering) that contributes to dispersion has been considered explicitly. Horizontal and vertical transverse dispersivity (α_y) were taken as 0.75m, and molecular diffusion is ignored. The biodegradation rate in all layers and zones was set as 0.001 day^{-1}. These parameter values are listed in Table B-9.

Table B-9 Input parameters for contaminant transport modeling

	Layer 1		Layer 2
	Zone I	Zone II	
Effective Porosity, n_e	0.2	0.2	0.2
Longitudinal Dispersivity, α_L *(m)*	15	15	15
Transverse Dispersivity, α_T *(m)*	0.75	0.75	0.75
Biodegradation Rate, λ (day^{-1})	0.001	0.001	0.001

B.5.3 Model Calibration

A calibration effort in this case would involve systematically adjusting the values of effective porosity, dispersivities (α_L, α_T), biodegradation rate (λ), in successive simulations, and comparing the results against the observed concentration at the monitoring wells. The transport model has not been fully calibrated. As the model now stands, the gross plume shapes from the simulations can be compared with mapped contamination from the field data. Actual site monitoring data show that benzene has never been detected in the monitor wells along Iowa Street, one block north of the LUST sites. Nor has it been detected in monitor wells between LUST site 8LTZ58 and city well #3 which facts provide constraints on plume spreading. With a calibrated model, evolution of the benzene plume could be simulated with greater confidence, and predictions about plume behavior could be made.

Figure B-5a illustrates the benzene plume in both layers after 10 years using the parameters listed in Table B-9. Figure B-5b is a close view of the plume. A large plume is formed due to the two sources at the two LUST sites of 8LTA75 and 7LTB86 and a small plume due to the LUST site of 8LTZ58. The plume boundary is set at the concentration of 100 ppb due to the accuracy of the numerical scheme used in the MT3DMS. The maximum length and width of the large plume are listed in Table B-10. The plume is moving towards well #3 due to its direct down gradient position from the LUST sites. Pumping of well #3 draws the plume down to the well screen in Layer 2. Wells #1 and #2 are not polluted even they are also pumped at rates comparable to well #3. The benzene plume at Ida Grove is much larger than that at Climbing Hill because the two layers at Ida Grove are much more permeable than those at Climbing Hill. The simulation results show that at Ida Grove, the plume became stable in just two years, as the length and width of the plume stay almost the same after two years in both layers.

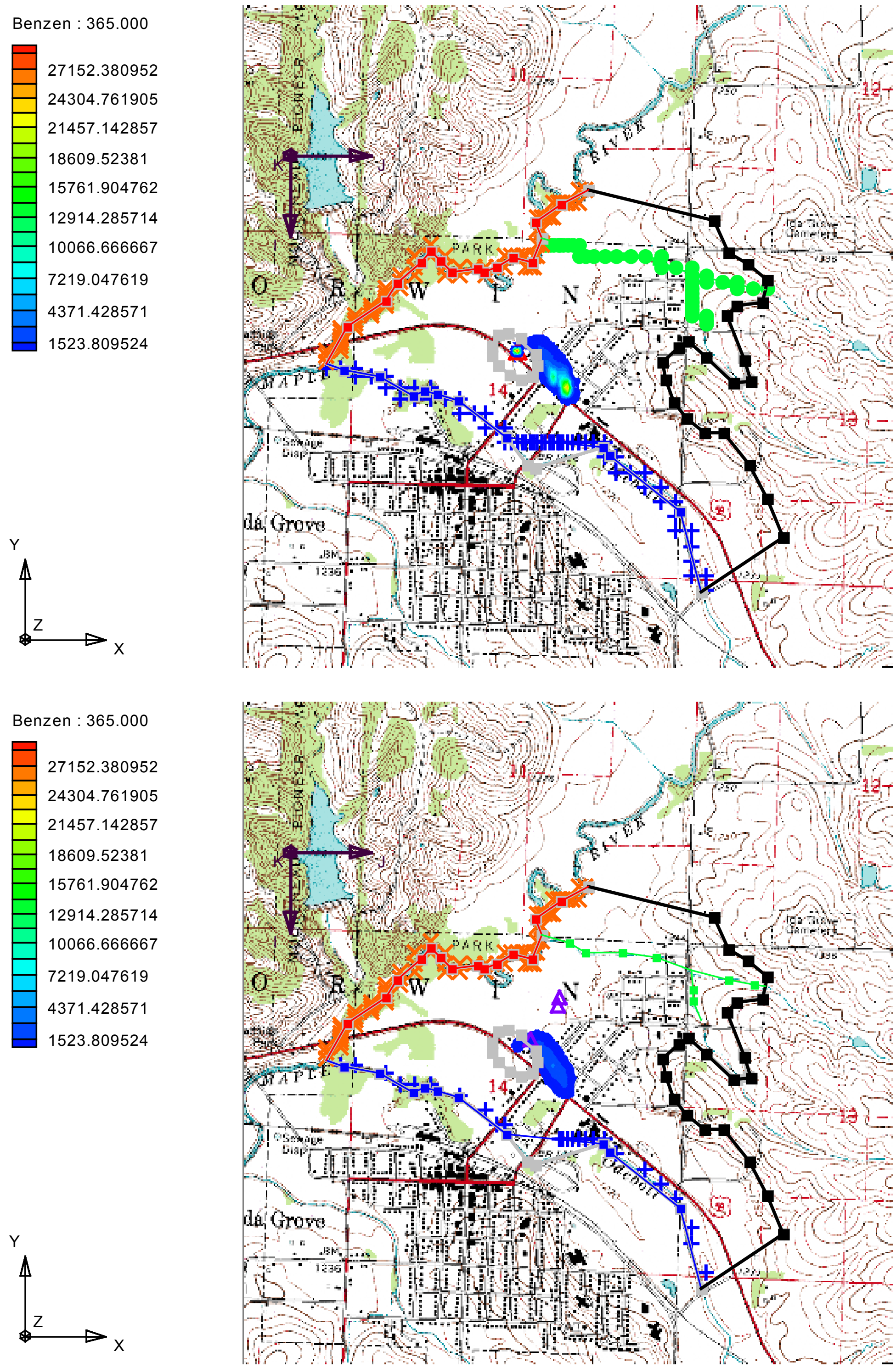
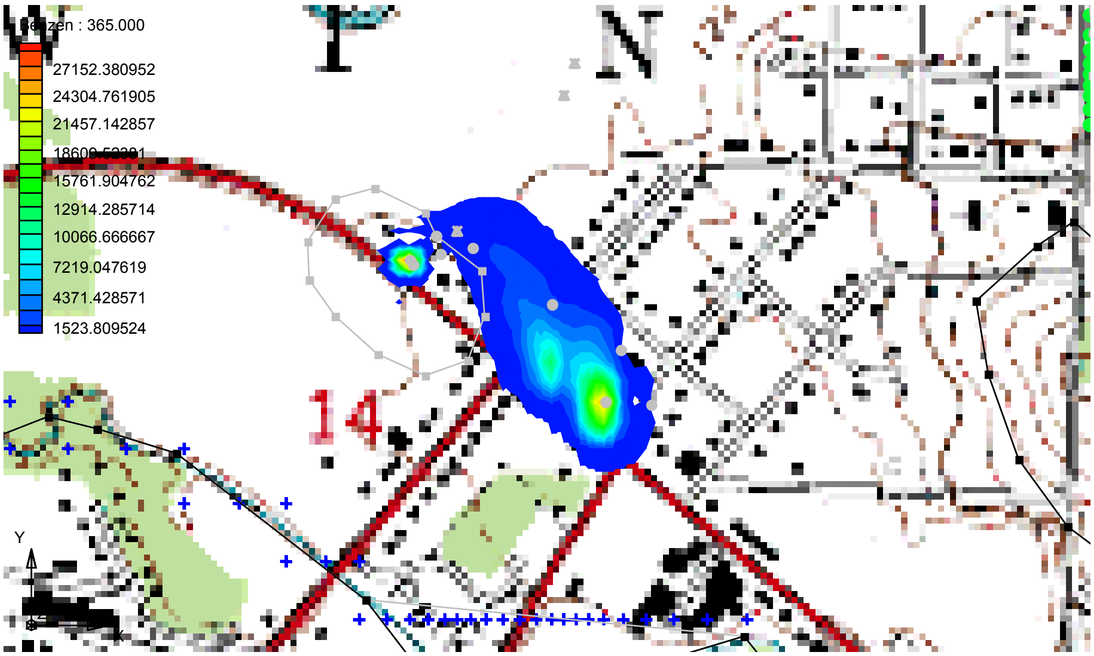


Figure B-5a Benzene concentrations at 3650 days in layer 1 (top) and in layer 2 (bottom)



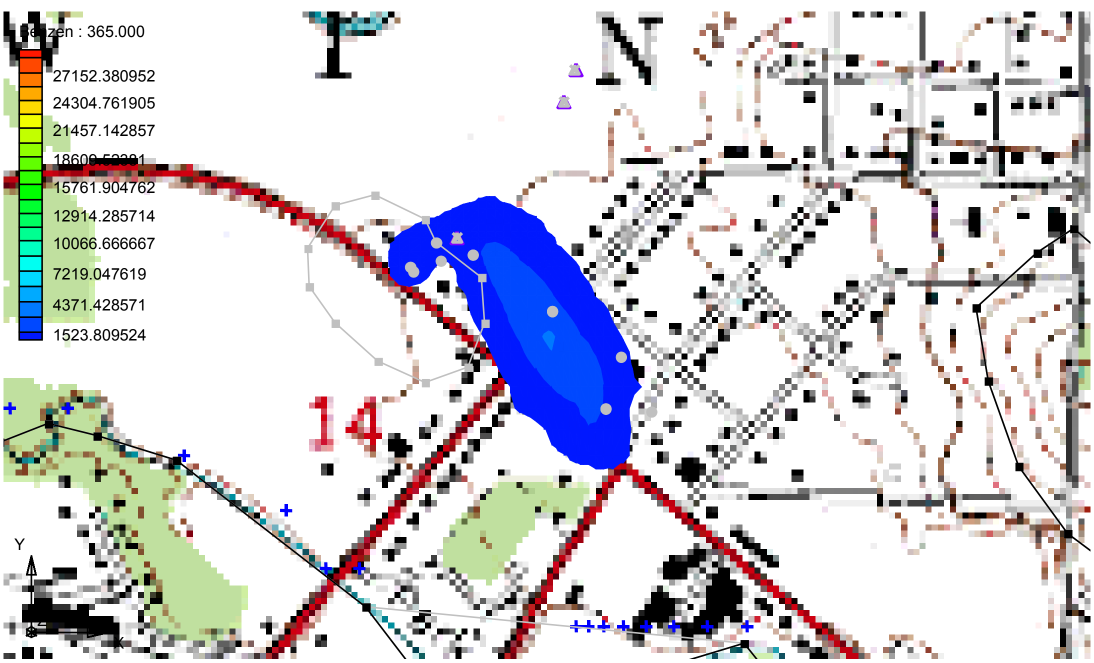


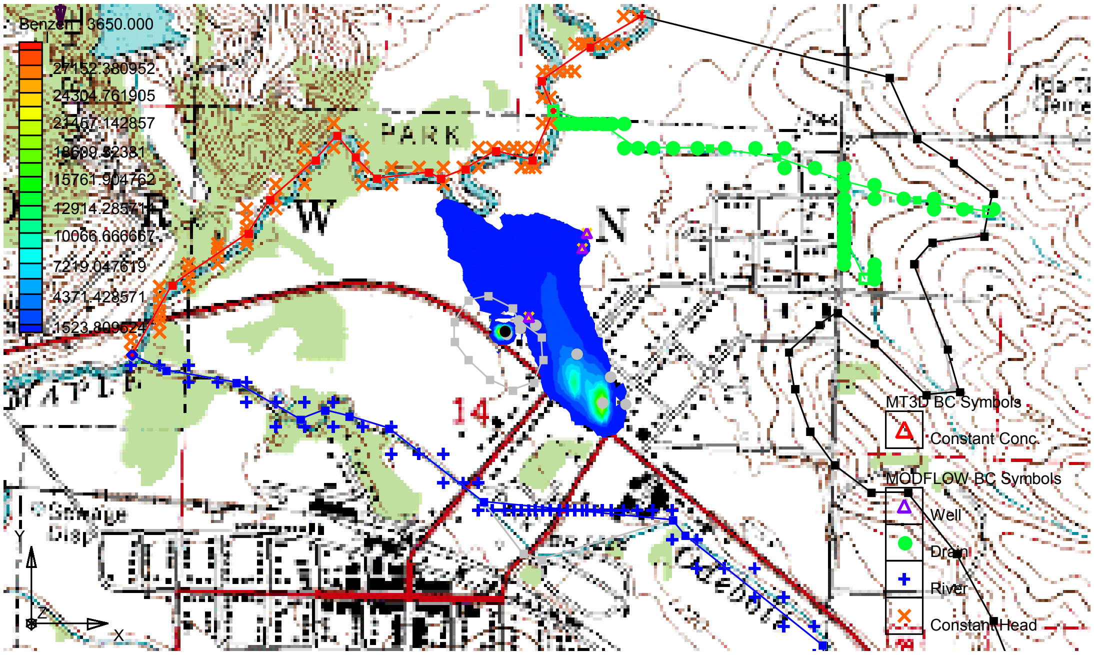
Figure B-5b Close view of benzene concentrations at 3650 days in layer 1 (top) and in layer 2 (bottom)

Table B-10 The length and width of the benzene plume at different times

Time (year)	Layer 1		Layer 2	
	Length	Width	Length	Width
1	394	167	366	154
2	401	176	404	155
3	406	176	406	156
5	406	179	404	155
10	406	179	406	155

B.5.4 Predictive Simulation

The scenario that city well #3 is shut off while both well #1 and #2 remain pumping, was simulated. Simulating this condition gives an idea of the hydraulic effect well #3 has on the plume, and an idea of the risk to wells #1 and #2. Figure B-6 illustrates the benzene plume in both layers after 10 years using the same parameter values used for Figure B-5. It is seen that without being captured by the well #3, the benzene plume migrated much further down gradient and dispersed wider towards wells #1 and #2. Both of the two wells would probably become contaminated by benzene if this case was put into practice.



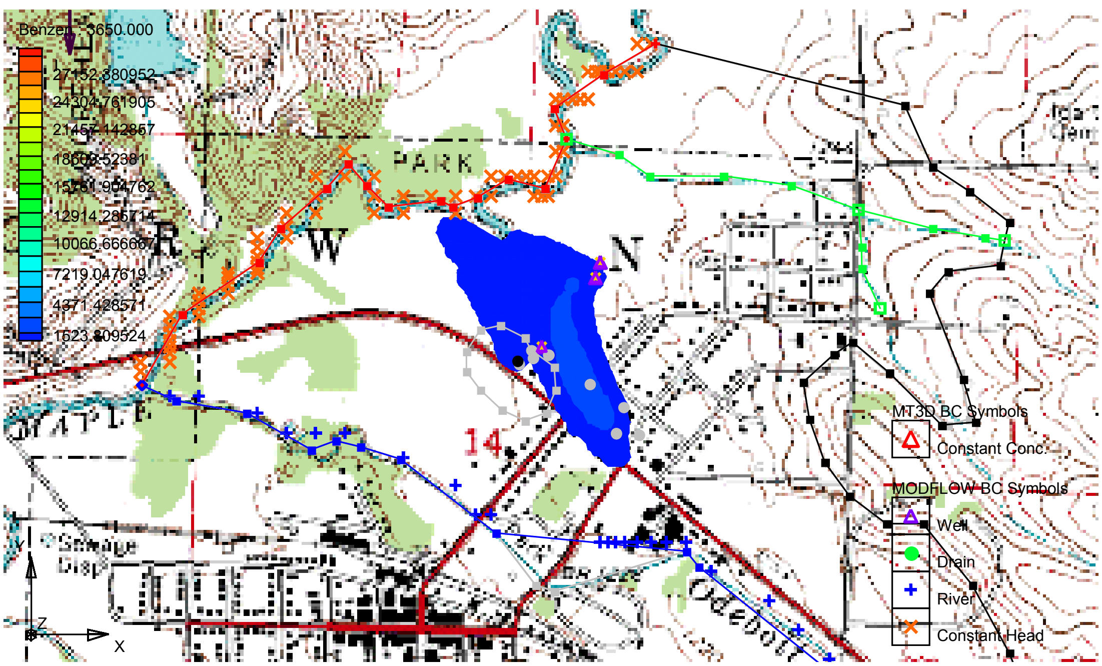


Figure B-6 Benzene concentrations at 3650 days in layer 1 (top) and in layer 2 (bottom) when Well #3 is not pumping

B.6 Summary and Conclusions

Groundwater flow in the neighborhood of the petroleum plumes and the city water wells is generally toward the NW, and appears to be controlled mainly by hydraulic connection between the aquifer and Odebolt Creek on the south, and hydraulic connection between the aquifer and the Maple River on the west. The regional groundwater flow for the area is northwestward, through the LUST sites and toward city well #3. With no wells pumping, city wells #1 and #2 are located off the groundwater flowpath that passes through the LUST sites. With the caveat that the transport model has not been calibrated, the model appears to demonstrate that if city well #3 is shut off, while wells #1 and #2 remain pumping, the latter wells would be expected to capture the contaminant plume from the LUST sites although concentrations reaching the well screens would likely be low. The groundwater flow direction from LUST site 8LTZ58 is dominantly vertical. Any leakage of petroleum downward through the clay layer at LUST site 8LTZ58 will contaminate the aquifer at a point within the radius of influence of city well #3.

C. Cook Park, Sioux City

C.1 Statement of Problem

Sioux City is located in northwestern Woodbury County of Iowa. The Cook Park neighborhood of Sioux City is located in the drainage of Perry Creek, about ¾ of a mile north of the Missouri River, and 1 ½ miles west of the Floyd River (Figure C-1). Two wells that are important components of the Sioux City water supply are located in Cook Park. Both of these wells produce from the Cretaceous Dakota Fm. and are cased through the overlying Quaternary alluvial gravel. A third well of similar construction is planned for the vicinity. Petroleum contamination as MTBE was detected in one of these wells in 2000, and has persisted in

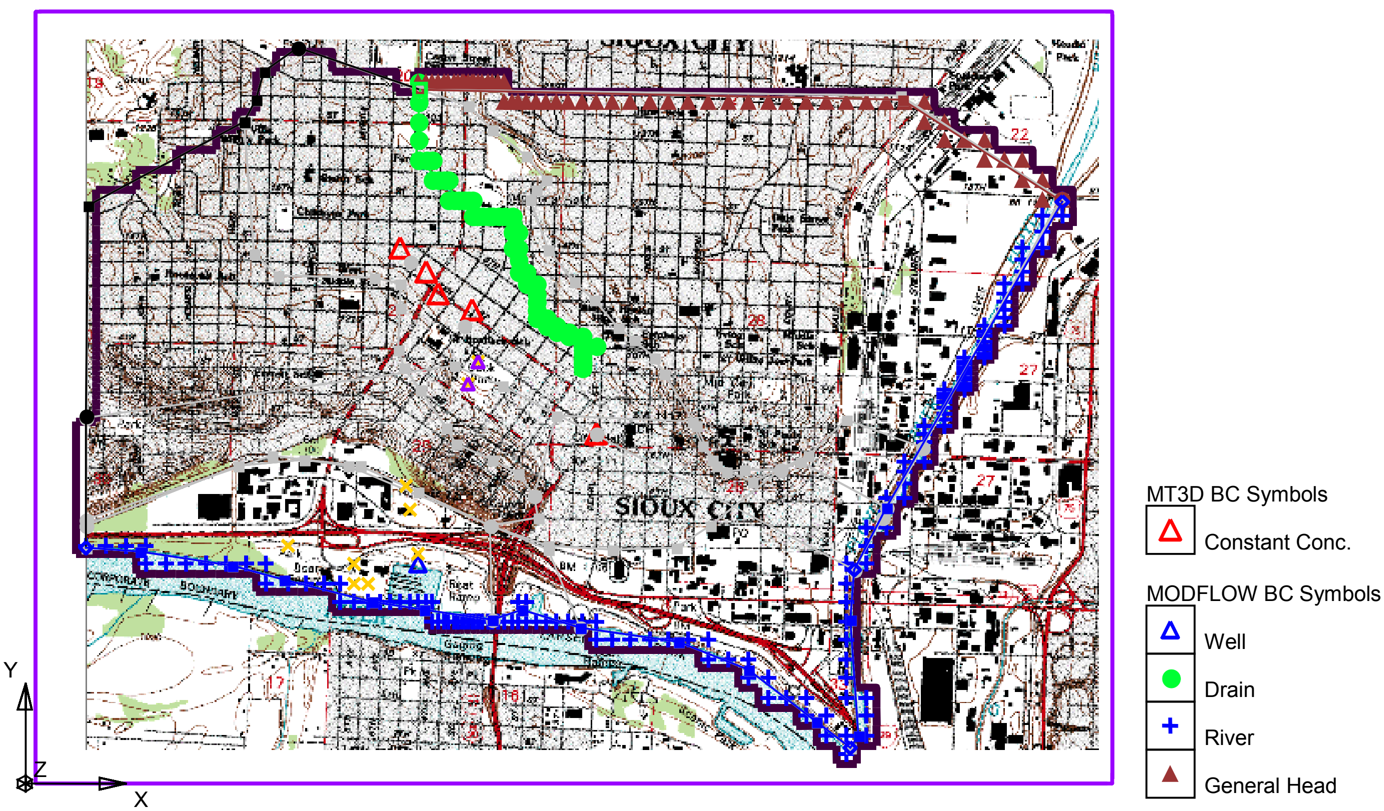


Figure C-1 The simulation domain with wells and sources for Cook Park has 11 operating wells that variously produce from Holocene alluvium and/or underlying Dakota Fm. The Quaternary Age units near the Missouri River are interpreted to be hydrologically subsequent water samples. Another well field for Sioux City is developed on the Missouri River flood plain about ½ mile south of Cook Park. This well field is known as the Riverfront field and separated from the units in Cook Park by an intervening remnant of low-permeability till. Farther to the east, near downtown Sioux City, the Quaternary Loess and alluvial units are interpreted to be hydrologically connected to the Missouri River alluvium.

An important question that is yet unanswered for security of the Sioux City water supply is whether or not the Dakota aquifer is confined at Cook Park. A second question of equal importance is whether the well casing through the gravel aquifer is intact or compromised. Petroleum contamination is known to occur at several LUST sites to the north, northwest and east of Cook Park.

C.2 Objectives

The purpose of modeling groundwater and contaminant transport at Cook Park was to determine:

1) the groundwater flow system that exists between the existing two-well field and the surrounding LUST sites;
2) what forms the MTBE and benzene plumes can be expected to have; and
3) what the effect on contaminant flow will be with addition of a third well in the vicinity.

C.3 Hydrogeologic Characterization

Maps, borehole logs, water level data, other hydrogeological information, and groundwater contaminant concentrations for Sioux City are taken from the IDNR LUST files #7LTT65, 8LTA40, 9LTA51, 7LTN10, 8LTX04, 8LTG66, 7LTQ55, 7LTI27, 8LTQ24, 8LTK38, 9LTI01, 8LTK62, 8LTJ27, 8LTW66, and 9LTC16. Additional hydrogeological and stratigraphic information was found in Munter *et al.*, 1983, and Burkart, 1984. Other borehole logs in the vicinity were obtained from IDOT (1979a, b; Iowa St. Hwy. Comm., 1957). Stratigraphic information in the Riverfront well field was also found in HDR Engineering (1998). Water well logs and some water production information are available on the internet at the IGSB GeoSam site (www.igsb.uiowa.edu/geosam_map). Water well construction diagrams and drillers logs for the Cook Park wells and the Riverfront wells were obtained from IDNR Field Office 3 (Spencer). Additional insights into the complex hydrostratigraphy of this region came from conversations with Prof. E.A. Bettis of the Univ. of Iowa Geoscience Dept., Drs. Brian Witzke and Greg Ludvigson, and Messers. Bob Libra and Bill Bunker of IGSB, and Mr. Richard Hammond of Hammond Wetmore Drilling, Vermillion, SD, and Mr. Brian Norton of Olsson Environmental Sciences, Omaha, NE.

Sioux City is at the boundary between the Loess Hills and Missouri River Alluvial Plain landform regions. Loess hills underlain by Cretaceous age formations separate the Cook Park neighborhood from the Big Sioux River, more than 3 miles to the west. The area is in a stratigraphically complex region that records many periods of late Quaternary age glacial and alluvial deposition on surfaces sculpted by erosion. Bedrock stratigraphy beneath the Quaternary section includes the Dakota Fm., and, in places, the overlying Graneros Fm., and is also modified by an erosional surface. Stratigraphic control is moderately good in the region, but lateral changes within the Cretaceous and Quaternary units, and the many erosional surfaces within the section make correlations difficult. In the Cook Park vicinity the Quaternary-Cretaceous contact is mapped as about 165 ft below ground surface and the uppermost Cretaceous unit is the Dakota Fm. (Witzke and Ludvigson, written and verbal communication, March, 2001).

One or more Pre-Illinoian tills are present above the Dakota Fm. in the Sioux City area. The glacial deposits are cut out in many places, but are generally overlain by alluvial sands and gravels of the Noah Creek Fm. Peoria Fm. loess generally overlies the Pleistocene age alluvial deposits and is about 40 ft thick at Cook Park. Holocene age erosion and sedimentation have greatly modified the loess deposit, cutting it out of the section in some places, and burying it with alluvial sands and clays in other places. At Cook Park, the Quaternary section has loess and alluvium beneath thin topsoil and irregular deposits of fill. This is underlain by Noah Creek sand that grades downward to gravel. Pre-Illinoian till underlies the gravel, and sandstone and shale of the Dakota Fm. occur immediately below that.

In general, groundwater in both the shallow alluvial aquifer and deep Dakota sandstone flows towards the Missouri River. Annual recharge to the water table is not precisely known, but is likely in the range of 2 to 6 inches (0.051 – 0.152 m/y) or 7 – 25 % of annual precipitaion. The depth to the water table in the Cook Park vicinity is about 40 ft, near the contact between the loess and underlying sands and gravels.

C.4 Groundwater Flow Modeling

C.4.1 Conceptualization and Design

The simulation domain is show in Figure C-1. The south and east boundaries are formed by the Missouri River and Floyd River, respectively, both of them are simulated with the River package in MODFLOW (the blue pluses in Figure C-1). The Missouri River flows from west to east and its stage at the entering and exit point of the domain are 323.0 m and 322.3 m, respectively. The boundary to the north is modeled with the general head boundary package in MODFLOW (the brown triangles in Figure C-1) since neither a physical or hydraulic boundary exists in this area. The boundary to the west is treated as no-flow boundary because it is a topographic divide for the shallow, alluvial aquifers, and is parallel to the direction of groundwater flow, i.e., it is a flowline, for the deeper Dakota aquifer.

A three-dimensional, four-layer, steady-state model of the Cook Park vicinity was constructed to examine hydraulic behavior and contaminant transport in the upper aquifer of the Dakota Fm., an overlying confining layer, if present, and the overlying alluvial sand and gravel. Figure C-2 is a simplified north-south hydrogeological cross section through Cook Park, showing the model layers and well positions.

The simulation domain is divided into an irregular grid which is refined at the two wells (Table C-1). The active cells consist of 46 rows, 45 columns, and 4 layers and are shown in Figure C-3.

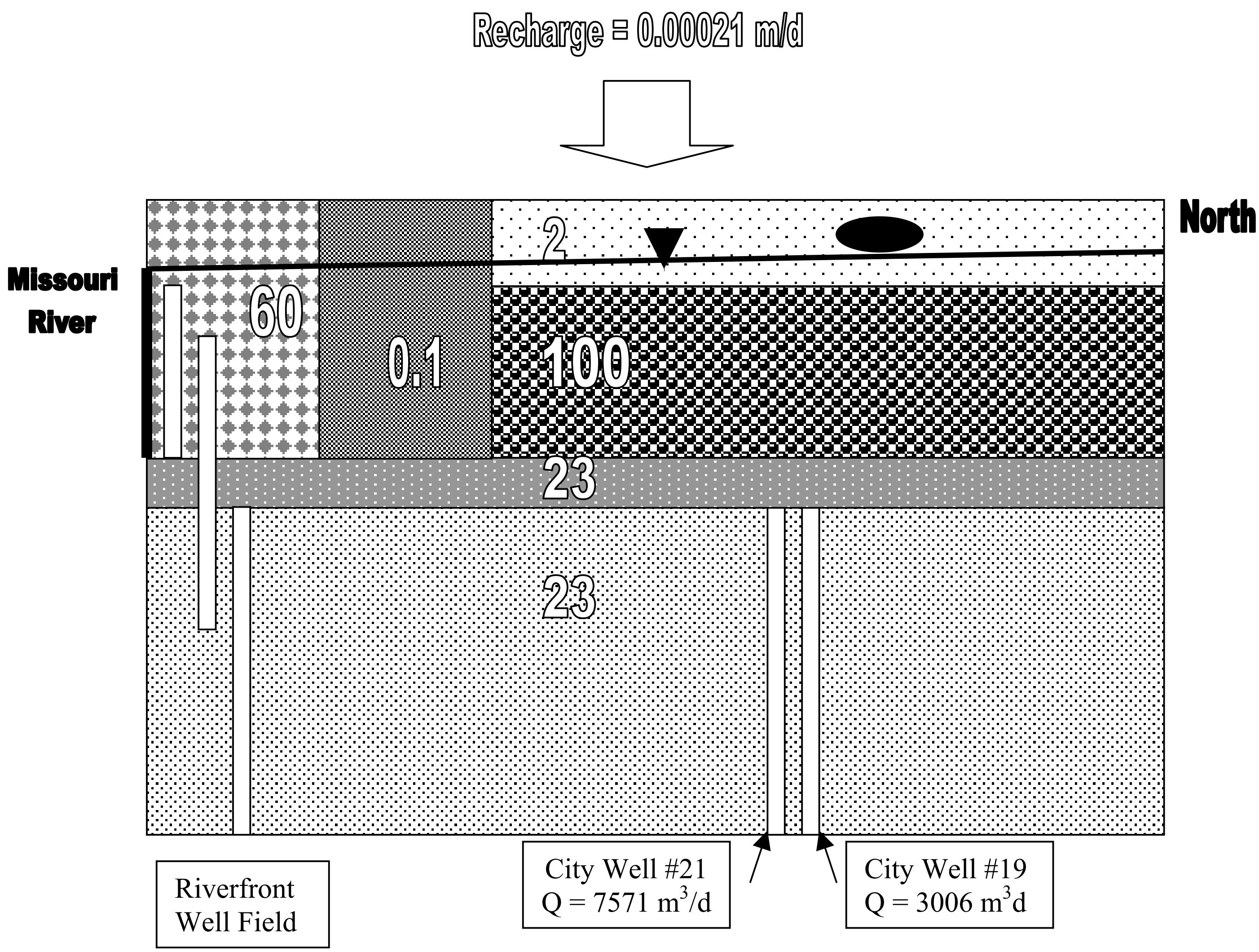


Figure C-2 Schematic N-S cross section of the Cook Park conceptual model. Not to scale. Black triangle denotes water table; black oval denotes petroleum source. Numbers within various fields are hydraulic conductivity (m/d) for the unit indicated.

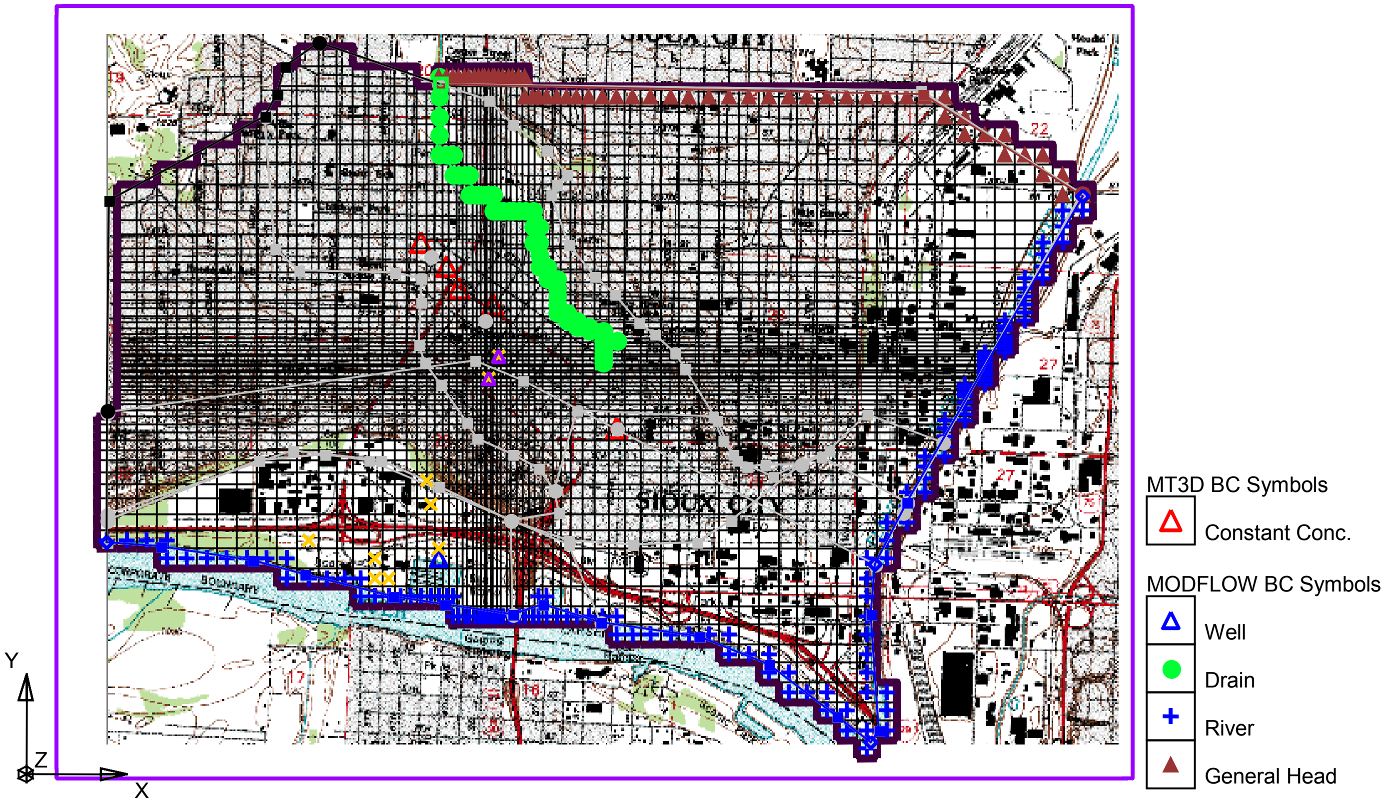


Figure C-3 Finite difference grids of the modeling domain

Table C-1. Parameters for grid refinement at the two wells.

Well #	Refine grid in X direction			Refine grid in Y direction		
	Base cell size	**Bias**	**Max cell size**	**Base cell size**	**Base**	**Max cell size**
19	15	1.1	100	15	1.1	100
21	N/A	N/A	N/A	15	1.1	100

C.4.2 Input Parameters

Six coverages for the model domain, Source/Sink, Layer 1, Layer 2, Layer 3, Layer 4, and Recharge, are created in GMS. The packages used in MODFLOW are: Basic, BCF, Well, Drain, General Head, Recharge, PCG2, and Output Control. The input parameter values for the

Source/Sink coverage are listed in Table C-2 and C-3. The Missouri River and Floyd River are simulated with the river package while Perry Creek is modeled with the drain package, even though water table evidence indicates Perry Creek is not an important hydrological feature with respect to the groundwater. Values of the river stage, bottom elevation, and conductance are given in Table C-2. Table C-3 provides the locations and pumping rates for the ten wells set in the model. Wells #7, #8, and #9 are screened in multiple layers, so their total pumping rate were distributed equally to the layers. This is an approximation of hydraulic behavior for the wells, and is a detail that can be further refined if necessary. Wells #1, #3, #4, #6 in the Riverfront field pump at negligible rates and were not included in the simulations. The large capacity collector well also in the Riverfront field is under direct influence of the Missouri River, and is not expected to affect the hydrologic regime in Cook Park appreciably. The proposed Dakota well in Cook Park is located about 400 ft east of well #21, and is expected, once approval is obtained from IDNR, to pump at a rate similar to well #21.

Table C-2. Input parameters for the rivers, creek, and general head boundary.

	Missouri River	**Floyd River**	**Perry Creek**	**General Head**
Simulated in MODFLOW by	River	River	Drain	General head
River stage *(m)*	327.3-328.0	327.3–328.0	N/A	N/A
Bottom elevation *(m)*	322.3- 323.0	322.3–325.0	335.3-336.8	326.8-328.0
Conductance (m/day)	30	30	5.0	0.5

Table C-3 Pumping well locations and rates

Well #	X *(m)*	Y *(m)*	I	J	K	Pumping Rate *(m^3/day)*
19	296708	4691732	29	36	4	-3006
21	296908	4691690	36	33	4	-7571
5	219010	4710114	51	21	4	-28.6
11	219026	4710000	53	22	4	-6242
10	218426	4709818	55	13	4	-922
2	218753	4709731	56	17	4	-1549
9	219068	4709774	56	23	1	-3.6
9	219068	4709774	56	23	2	-3.6
8	218755	4709636	57	17	2	-774
8	218755	4709636	57	17	3	-774
8	218755	4709636	57	17	4	-774
7	218823	4709629	57	18	2	-970
7	218823	4709629	57	18	3	-970
7	218823	4709629	57	18	4	-970

The hydrostratigraphy was simplified as a stack of layers of uniform thicknesses. This may be an oversimplification of the stratigraphy as discussed above, but the objectives of this modeling pertain to the vicinity of Cook Park, so the well control there was deemed to be most important for the model. Attempting to represent accurately the stratigraphy in more distant parts of the domain would add needless complexity to the model. Layer 1 represents a thin, unconfined zone that contains the contaminant sources. It is heterogeneous on a large scale and thus is divided into four zones (Figure C-4). This unit is typically a fine to medium grained alluvial sand, and might in some places include silts of the overlying loess. The main thickness of the loess and Holocene alluvial deposits around Cook Park are in the unsaturated zone and so cannot be modeled with MODFLOW and MT3D. Deposits of till are known to occur between Cook Park and the Riverfront field to the south, so a low permeability zone was set in layer one, separating the two areas. Stratigraphy to the east of Cook Park is not well known, and the influence of the Floyd River on the unconfined aquifer is likewise not well known. Consequently, the simulated results on that side of the model are assumed to be of doubtful accuracy. Because the Quaternary sand and gravel unit represented by layer 2 is the same formation (Noah Creek) as that for which pump tests are available from Ida Grove, a comparable hydraulic conductivity of 100 m/d was assumed. Layer 3 was divided into two zones (Figure C-4) where Zone II, with a small K value of 0.23 m/d, is included to simulate the effect of a confining layer above the Dakota aquifer. Layer 4 represents the upper productive part of the Dakota aquifer, across which the city wells are screened. A hydraulic conductivity of 23 m/d was assigned to this layer. That K value is the average of reported K's for the Dakota regionally (Munter *et al*, 1993). The aquifer type, top and bottom elevation, and horizontal and vertical hydraulic conductivity for each layers and zones are listed in Table C-4. These values are estimated based on available data.

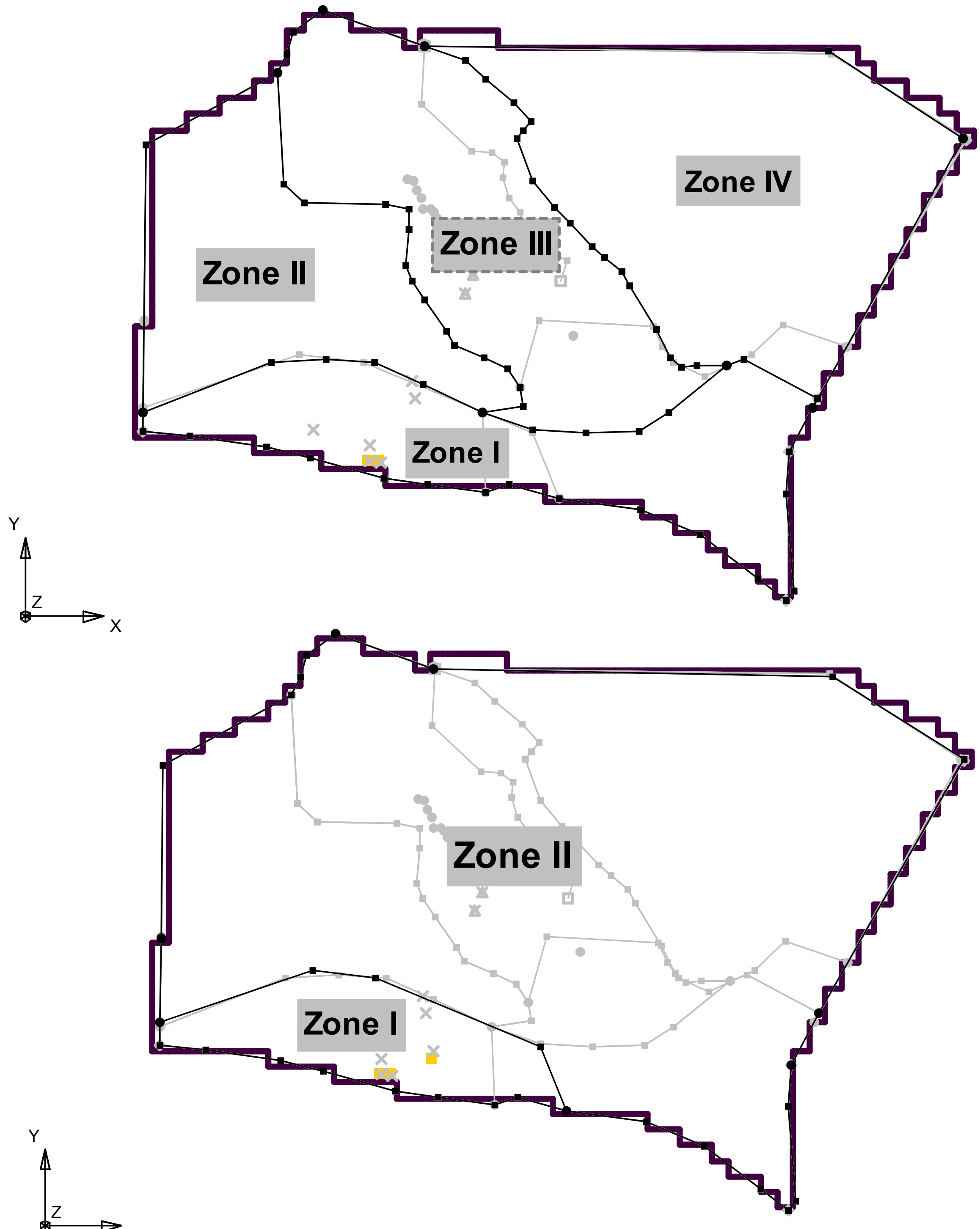


Figure C-4. Hydraulic conductivity zones of layer 1 and 2 (top) and layer 3 (bottom) (ignore the light green or gray lines)

Table C-4 Input parameters of the layers and zones for groundwater flow modeling

Well #	**Zone #**	**Aquifer Type**	**Top Elevation *(m)***	**Bottom Elevation *(m)***	K_h *(m/d)*	K_v *(m/d)*	**Recharge Rage *(m)***
Layer 1	I	Unconfined	342	320	60	60	0.00042
	II	Unconfined	342	320	0.1	0.1	0.0001
	III	Unconfined	342	320	2.0	2.0	0.00042
	IV	Unconfined	342	320	1.5	1.5	0.00042
Layer 2	I	Confined	320	289	0.1	0.1	N/A
	II	Confined	320	289	100	100	N/A
	III	Confined	320	289	1.5	1.5	N/A
	IV	Confined	320	289	60	60	N/A
Layer 3	I	Confined	289	284	23	23	N/A
	II	Confined	289	284	0.23	0.23	N/A
Layer 4	N/A	Confined	284	110	23	23	N/A

C.4.3 Model Calibration

The flow model is calibrated by changing the hydraulic conductivity, the net recharge rate, and the conductance of the two river beds, and comparing results with the long-term average of the observed hydraulic heads at eleven monitor wells. The available monitor wells only go a few feet deeper than the water table, so calibration could not be done for the deeper layers. The calibration target is set to be within 0.5 m of the observed water levels and the results are listed in Table C-5. Information was not obtained regarding the pumping water levels in wells 19 and 21. Once this information becomes available, additional calibration of layer 4 will be possible. The calibrated conductance values are listed in Table C-2, the calibrated hydraulic conductivity values are listed in Table C-4, and the calibrated net recharge rate is 0.00021 m/day (3 in/yr). The calibrated steady-state head contours are illustrated in Figure C-5 along with a scatter plot of the observed vs. modeled head at the four monitoring wells and the error summary. The calibration is excellent: all errors are smaller than 0.5 m and the RMSE is only 0.24.

Table C-5 Calibration results for hydraulic heads at observation wells

Well #	**X** *(m)*	**Y** *(m)*	**I**	**J**	**K**	**Observed head** *(m)*	**Simulated head** *(m)*	**Error** *(m)*
MW-6	218980	4711321	13	21	1	326.90	326.77	-0.13
MW-8	219017	4711294	13	22	1	327.10	326.76	-0.34
MW-14	219033	4711234	14	22	1	326.80	326.75	-0.05
MW-25	219061	4711185	15	23	1	327.00	326.78	-0.22
RMW-8	219120	4711127	16	24	1	326.70	326.69	-0.01
RMW-12	219140	4711107	16	25	1	326.70	326.68	-0.02
RMW-15	219158	4711065	17	25	1	326.50	326.66	0.16
RMW-16	219203	4711025	18	27	1	326.70	326.64	-0.06
RMW-18	219071	4711125	16	23	1	326.70	326.70	-0.00
RMW-36	219307	4710916	21	32	1	326.20	326.60	0.40
SMC	219959	4710374	46	50	1	326.40	326.91	0.51
Root Mean Square Error = 0.24								

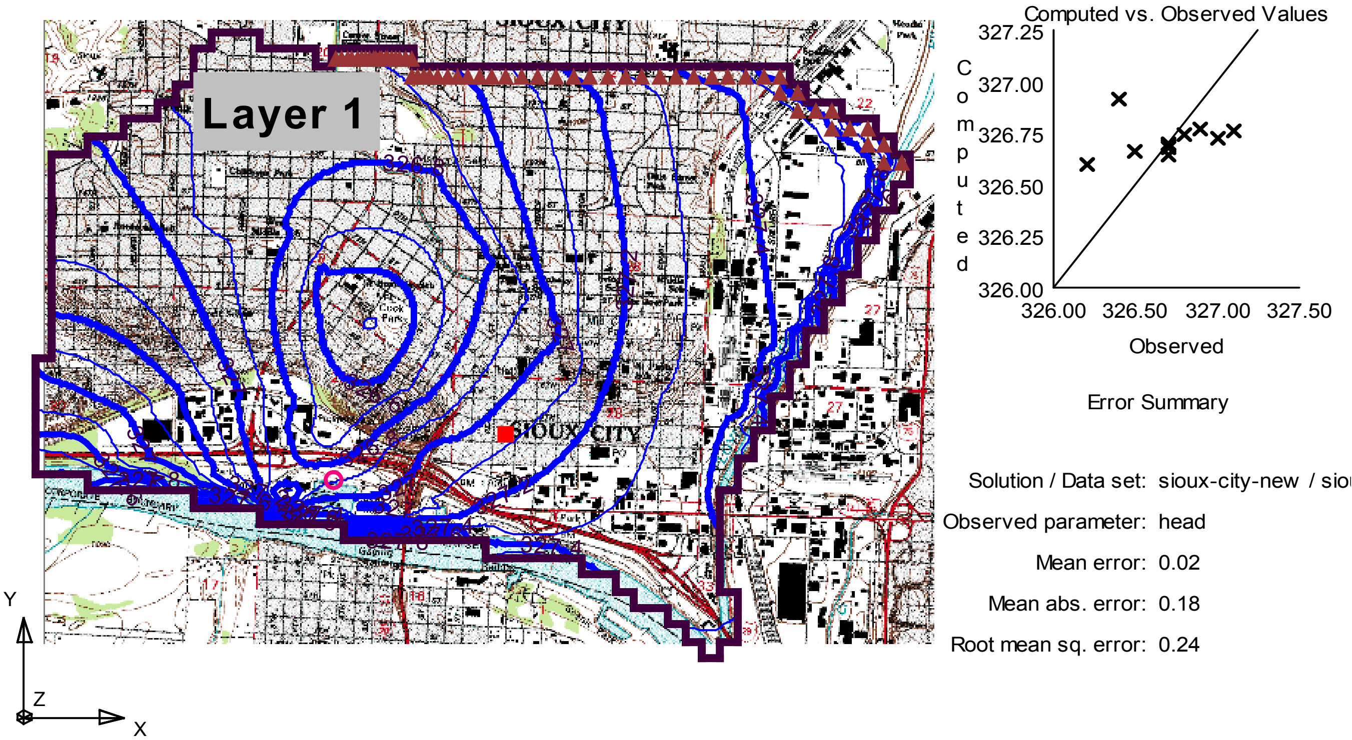


Figure C-5 Steady-state hydraulic head contours of Layer 1 at Cook Park (left) with scatter plot of simulated vs. observed heads at monitoring wells (right)

C.4.4 Sensitivity Analysis

A sensitivity simulation is carried out by changing the value of hydraulic conductivity of layer 3 from 0.23 to 23 m/d, i.e., assuming there is no confining layer between the alluvium and the Dakota formation. Comparison between the simulated and observed heads is given in Table C-6. It is seen that the hydraulic heads are not sensitive to this change. Most wells have more or less the same head values and the RMSE has the same value of 0.24 in Table C-5.

Table C-6 Comparison of the simulated and observed heads when K=23 m/d for layer 3

Well #	X *(m)*	Y *(m)*	I	J	K	Observed head *(m)*	Simulated head *(m)*	Error *(m)*
MW-6	218980	4711321	13	21	1	326.90	326.79	-0.11
MW-8	219017	4711294	13	22	1	327.10	326.78	-0.32
MW-14	219033	4711234	14	22	1	326.80	326.77	-0.03
MW-25	219061	4711185	15	23	1	327.00	326.74	-0.26
RMW-8	219120	4711127	16	24	1	326.70	326.71	0.01
RMW-12	219140	4711107	16	25	1	326.70	326.70	-0.00
RMW-15	219158	4711065	17	25	1	326.50	326.67	0.17
RMW-16	219203	4711025	18	27	1	326.70	326.65	-0.05
RMW-18	219071	4711125	16	23	1	326.70	326.72	0.02
RMW-36	219307	4710916	21	32	1	326.20	326.57	0.37
SMC	219959	4710374	46	50	1	326.40	326.93	0.53
Root Mean Square Error = 0.24								

C.5 Contaminant Transport Modeling

Contaminant sources exist in layer one of the model and include five known LUST sites within a few blocks around the Cook Park well field. A monitor well network exists for some of these LUST sites, but no recent data is available for others, and no shallow monitor wells currently exist in Cook Park. The contaminants of concern are benzene and MTBE from the three LUST sites. The plumes are simulated with MT3D in GMS v. 3.1 based on the steady-state groundwater flow condition obtained in Section C.4.

C.5.1 Model Conceptualization and Design

The simulation domain is the same shown in Figure C-1 with no solute flux across all the boundaries. Four contaminant sources were set in the model corresponding to highest reported benzene concentrations. These sources are at the LUST sites, 8LTA40, 7LTT65, and 7LTQ55, and are in a line along West 7th Ave, to the north and northwest of Cook Park. A fifth source, corresponding to the highest MTBE concentration in the vicinity, was set at the former location of LUST site 8LTK62, east of Cook Park. A weak MTBE source was also set at 7LTT65. The source concentrations are given in Table C-7. The LUST sites are treated as internal constant concentration sources, which represents a conservative scenario even though the times and amounts of petroleum releases from the sources are uncertain. Benzene and MTBE source concentrations are the highest reported concentrations from monitor wells at the individual sites. These were concentrations at the water table, some 30 ft below the LUSTs. Contaminated soil exists in the unsaturated zone between, but could not be modeled with this software.

Table C-7. Source locations and concentrations at the five LUSTs

LUST #	**X** ***(m)***	**Y** ***(m)***	**I**	**J**	**K**	**Benzene Concentration** ***(ppb)***	**MTBE Concentration** ***(ppb)***
8LTA40	218986	4711301	13	21	1	3,000	NA
7LTT65	219110	4711175	15	24	1	6,000	300
8LTE66	219173	4711072	17	26	1	4,000	NA
7LTQ55	219339	4710986	19	34	1	5,000	NA
8LTK62	219958	4710371	46	50	1	3,000	1700

C.5.2 Input Parameters

Four packages, Basic, Advection, Dispersion, and Chemical Reactions, are used in MT3D. Some of the parameters in the Basic package is listed in Table 8. The method of characteristics (MOC) is selected in the Advection package.

Table C-8. Stress period and time step information in Basic package of MT3DMS.

Stress period	Stress period length *(day)*	Max transport steps	Initial time step size	Time step bias	Max time step size
1	3650	20000	365	1	365

The other parameters needed in this simulation are effective porosity (n_e), dispersivity (α), and biodegradation rate (λ). Adsorption is neglegted in the coarse alluvial sand and gravel and in the Dakota Fm. sandstone. These parameters have not been determined from aquifer samples, so assumptions were based on the borehole log descriptions. The value for effective porosity is estimated to be 0.2. The value for longitudinal dispersivity (α_x) is estimated by noting the plume length from site 8LTA40 is about 550 ft, so the estimation formula of Neuman (1990) yields a value of 65 ft (20 m). However, the value of 15 m is used for α_x because part of large-scale heterogeneity (i.e., layering) that contributes to dispersion has been considered explicitly. Horizontal and vertical transverse dispersivity (α_y) were taken as 0.75m, and molecular diffusion is ignored. The biodegradation rate was set at λ = 0.001 /d. Slower biodegradation rate was assumed for the lower oxygen environment of the Dakota aquifer. These parameter values are listed in Table C-9. Note that Zone I of Layer 1 (clay till) has the same parameters as the aquifers, even though it has a much finer-grained texture. This is not reasonable assumption, but for these simulations transport in the till is not a concern in that Zone, so there is no effect in the model.

Table C-9 Input parameters the layers for contaminant transport modeling

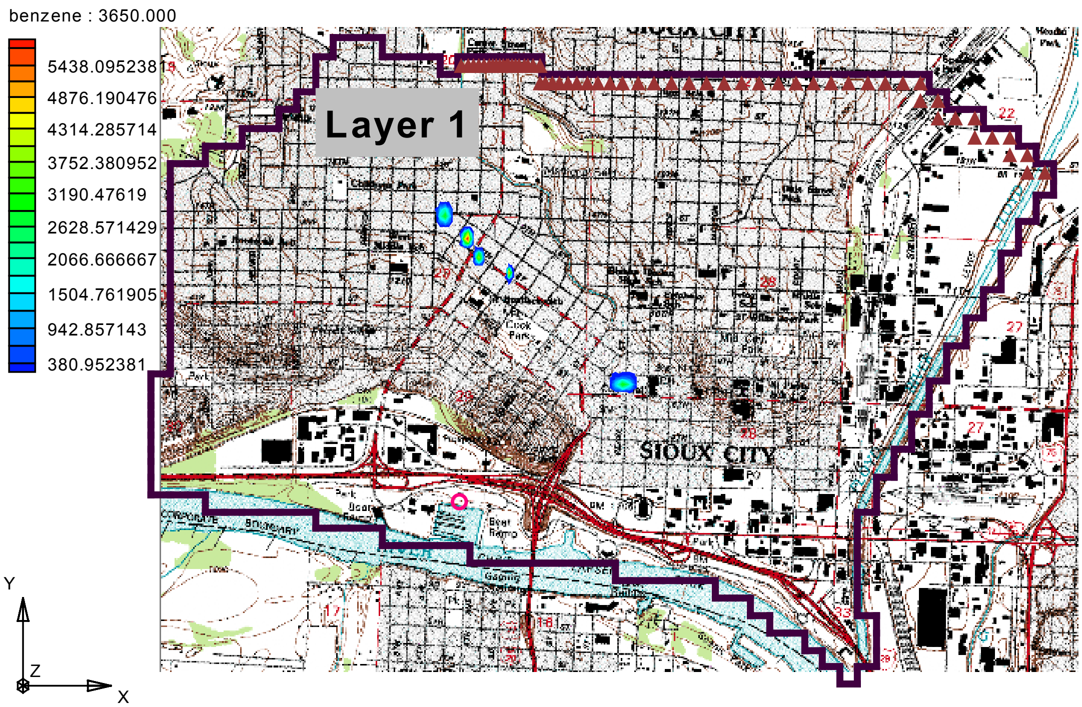
Well #	Zone #	Effective Porosity	Longitudianl dispersivity *(m)*	Transverse dispersivity *(m)*	Biodegradation rate for Benzene *(d^{-1})*	Biodegradation rate for MTBE *(d^{-1})*
Layer 1	I	0.2	20	1	0.001	0
	II	0.2	20	1	0.001	0
	III	0.2	20	1	0.001	0
	IV	0.2	20	1	0.001	0
Layer 2	I	0.2	20	1	0.001	0
	II	0.2	20	1	0.001	0
	III	0.2	20	1	0.001	0
	IV	0.2	20	1	0.001	0
Layer 3	I	0.2	20	1	0.0005	0
	II	0.2	20	1	0.0005	0
Layer 4		0.2	20	1	0.0005	0

C.5.3 Model Calibration

A calibration effort in this case would involve systematically adjusting the values of effective porosities, dispersivities (α_L, α_T), biodegradation rates (λ), (and giving some consideration to distribution coefficients (K_d), as well) for each layer in successive simulations, and comparing the results against the observed concentration at the monitoring wells. The transport model has not been fully calibrated. As the model now stands, the gross plume shapes from the simulations can be compared with mapped contamination from the field data. Actual site monitoring data show that benzene has never been detected in the water supply wells #19 and #21. With a calibrated model, evolution of the benzene plume could be simulated with greater confidence, and predictions about plume behavior could be made.

Figure C-6 illustrates benzene plumes in layers 1 and 2 from the five constant sources at the LUSTs (Table C-7) after 3 years, using the parameters listed in Table C-9. The five plumes remain separate from each other in layer 1 but some of them merged together in layer 2. All plumes stay almost the same or became stable after 3 years. None of the plumes migrates into layer 3 and thus layer 4 remains uncontaminated, too. This can be viewed as good news since both Well #19 and #21 are pumping from layer 4.

Figure C-7 illustrates the MTBE plume in the four layers from the two constant concentration sources (Table C-9) after 10 years. Figure C-7a is for layers 1 and 2 and Figure C-7b is for layers 3 and 4. This result indicates that the highly water soluble and recalcitrant MTBE can be expected to reach the well screens in the Dakota aquifer from sources of concentration in the range of 1000 ug/L.



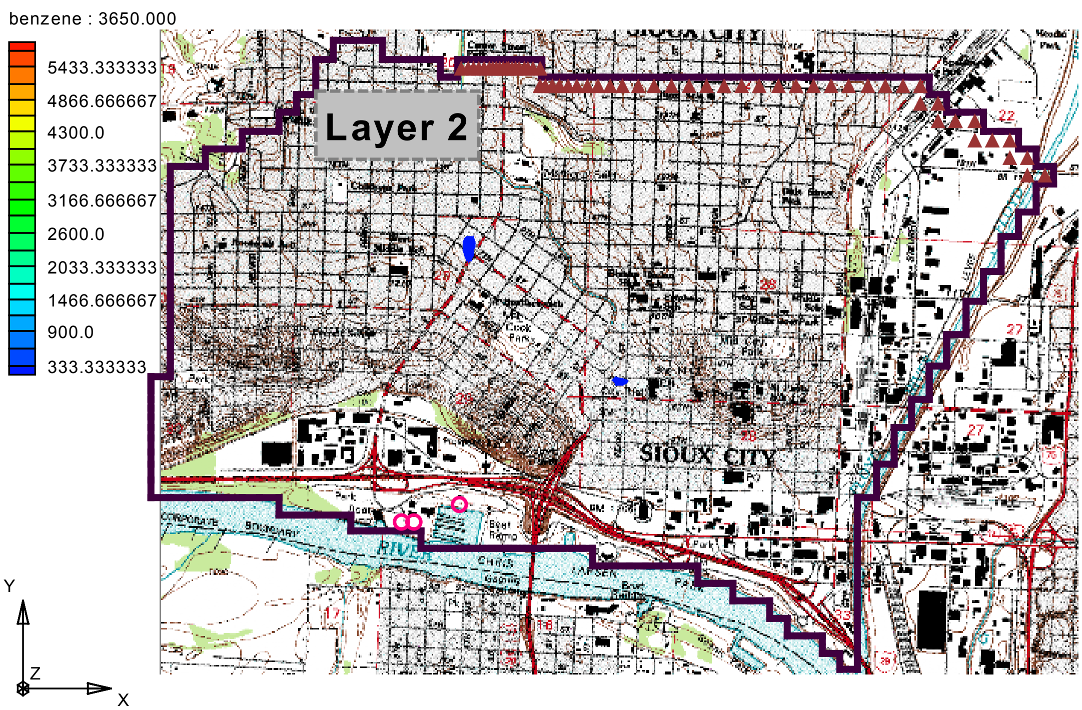


Figure C-6 Benzene concentrations at 10 years in layer 1 (top) and in layer 2 (bottom) at Cook Park (There is no benzene in layer 3 and 4).

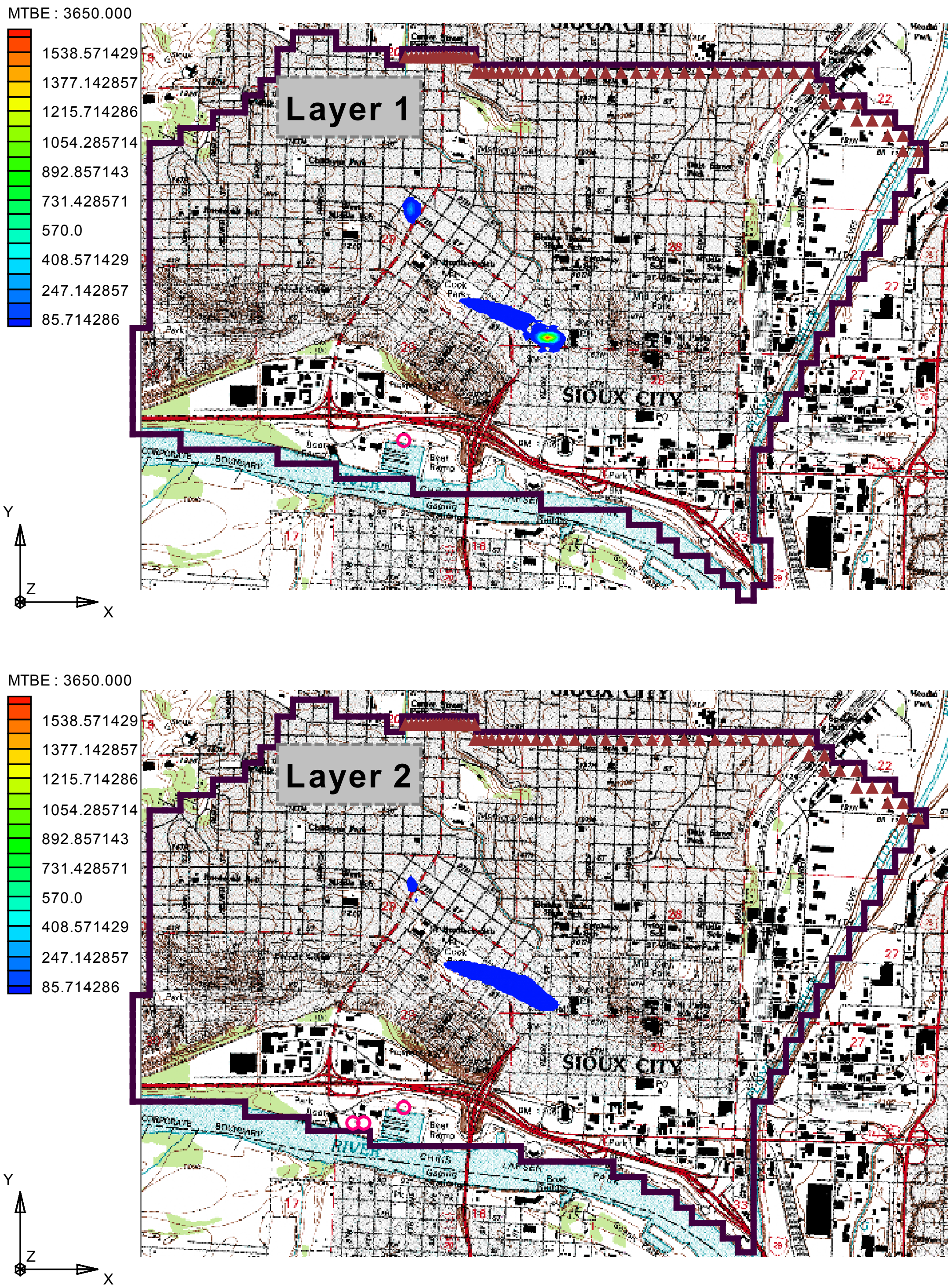
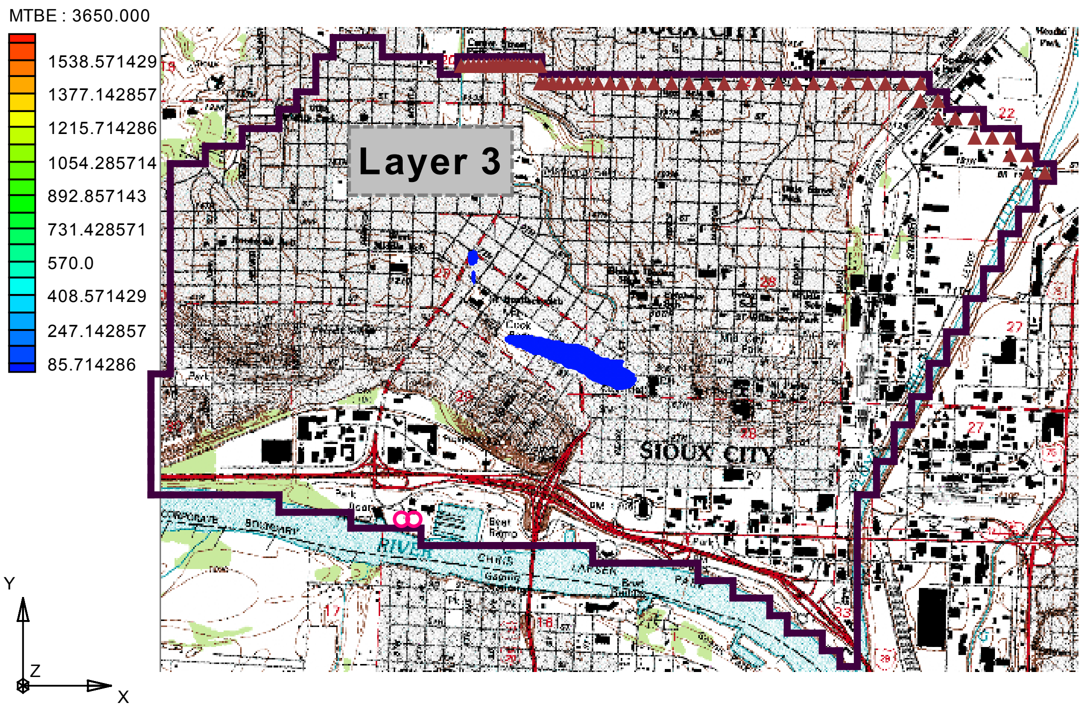


Figure C-7a MTBE concentrations at 3650 days in layer 1 (top) and in layer 2 (bottom) at Cook Park



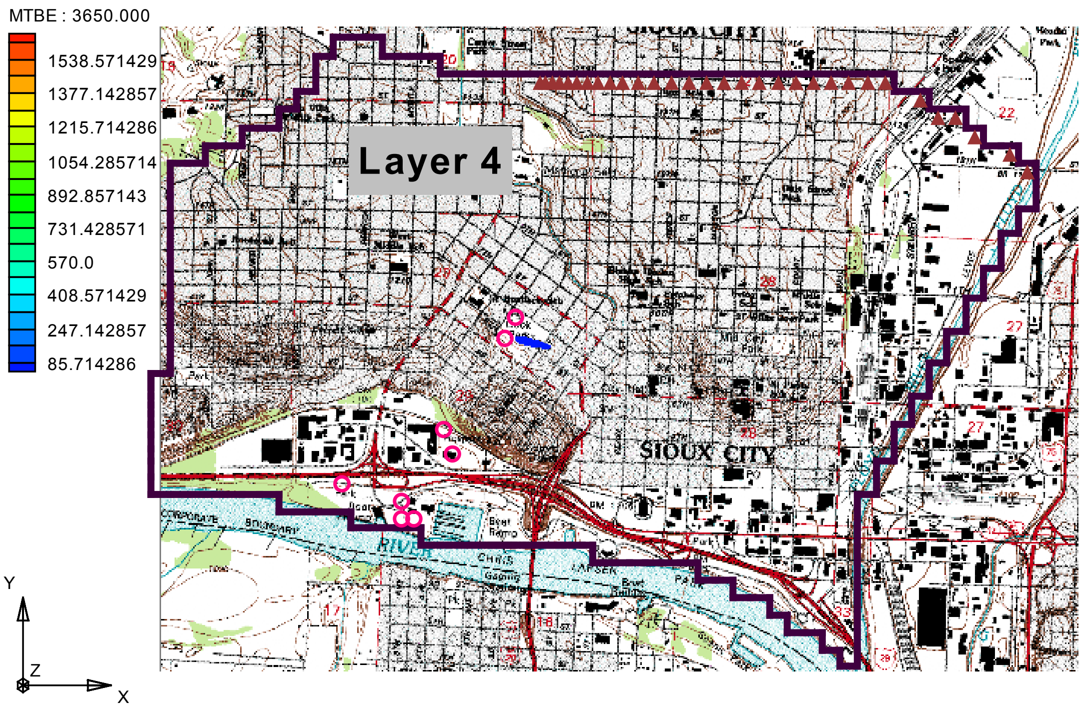


Figure C-7b MTBE concentrations at 3650 days in layer 3 (top) and in layer 4 (bottom) at Cook Park

C.5.4 Predictive Simulation

A new well will be drilled into the Dakota formation about 100 m to the southeast from Well #21. It will create additional drawdown around the Cook Park area and draw the contaminants to the well once it is pumped. Figure C-8 shows the hydraulic head contours when the new well is pumping. Figure C-9 presents the benzene plume in layers 1 and 2 and Figure C-10 gives the MTBE plumes in all four layers after 10 years based on the steady-state condition in Figure C-8. It is seen that the effect of the new well is not significant and the benzene and MTBE plumes in Figure C-9 and C-10 are similar to those in Figure C-6 and C-7, respectively.

C.6 Summary and Conclusions

The two existing water supply wells at Cook Park (#19 and #21) produce a large radius of influence in the alluvial aquifer and in the underlying Dakota aquifer. The full extent of the radius of influence is not well known due to the limited extent of the observation well network. The Riverfront well field exerts a minor influence on the hydraulic regime in the Cook Park neighborhood. That influence is limited to the Dakota Fm to the south of Cook Park. The petroleum plumes mapped in LUST site assessments to date shows only the water table manifestation of a much more complicated system. The effect of the Cook Park water wells is to draw-down the contaminant plume so that monitor wells that barely intersect the water table miss the contamination migrating at deeper levels.

Based on currently available sampling data, the source of the MTBE found in the Cook Park water wells could be the former LUST site 8LTK62, located to the east. The addition of a third water well to Cook Park similar to existing well #21 will cause the gradient to increase by about 60%, and will disturb the contaminant plume, possibly enhancing migration toward the wells.

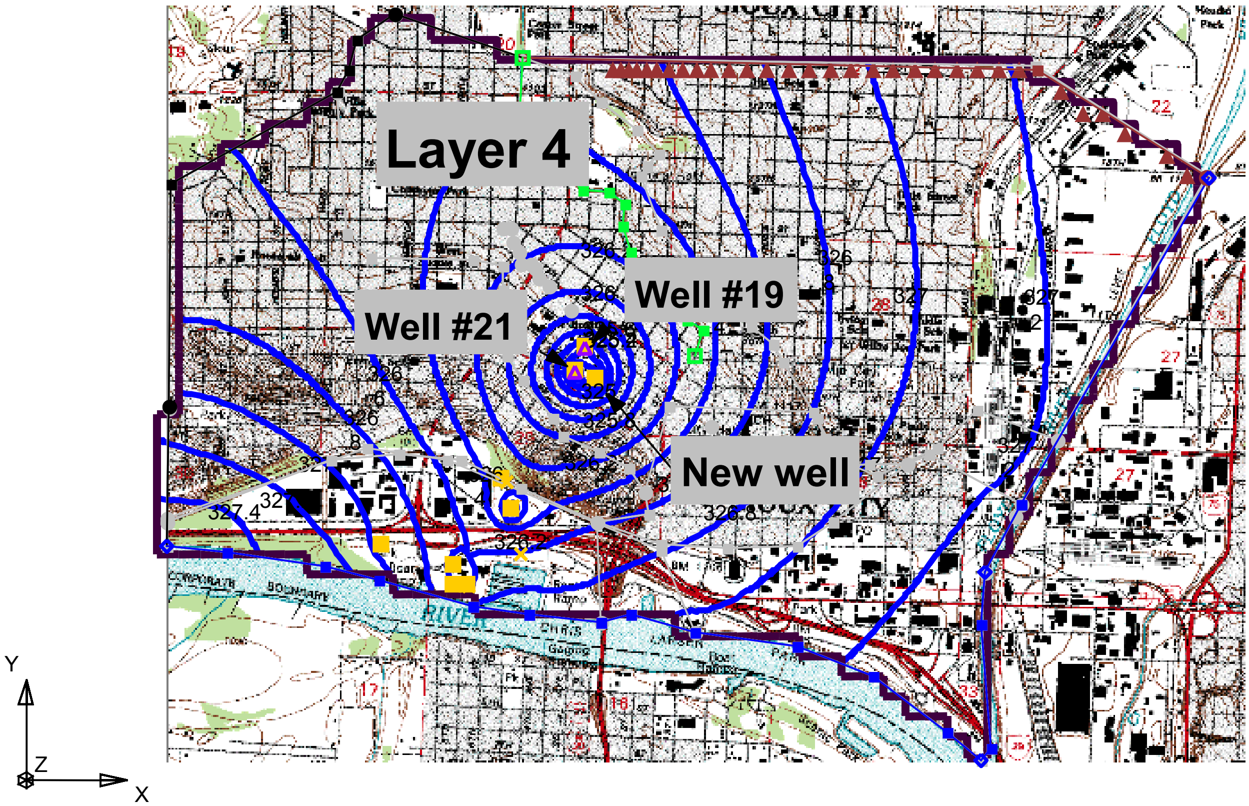
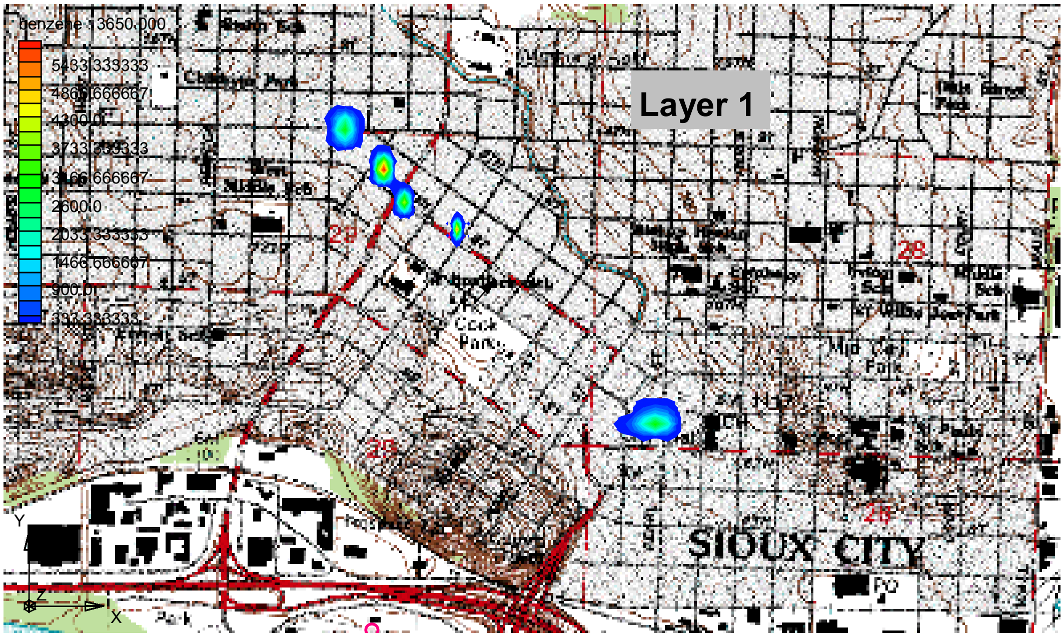


Figure C-8 Steady-state hydraulic head contours of Layer 1 at Cook Park with the proposed new well pumping at 7571 m^3/d



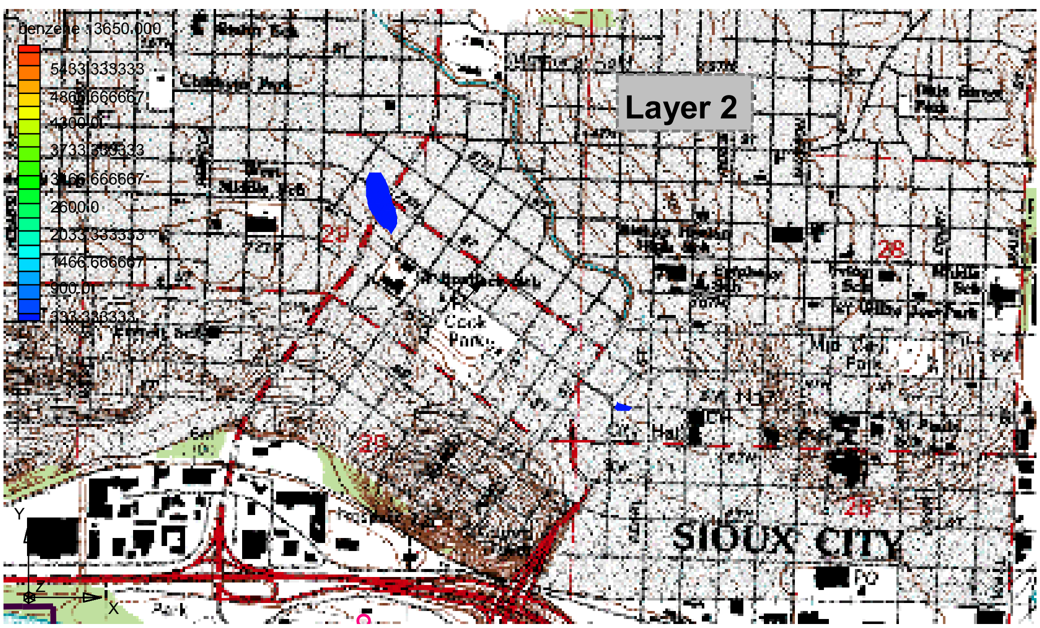
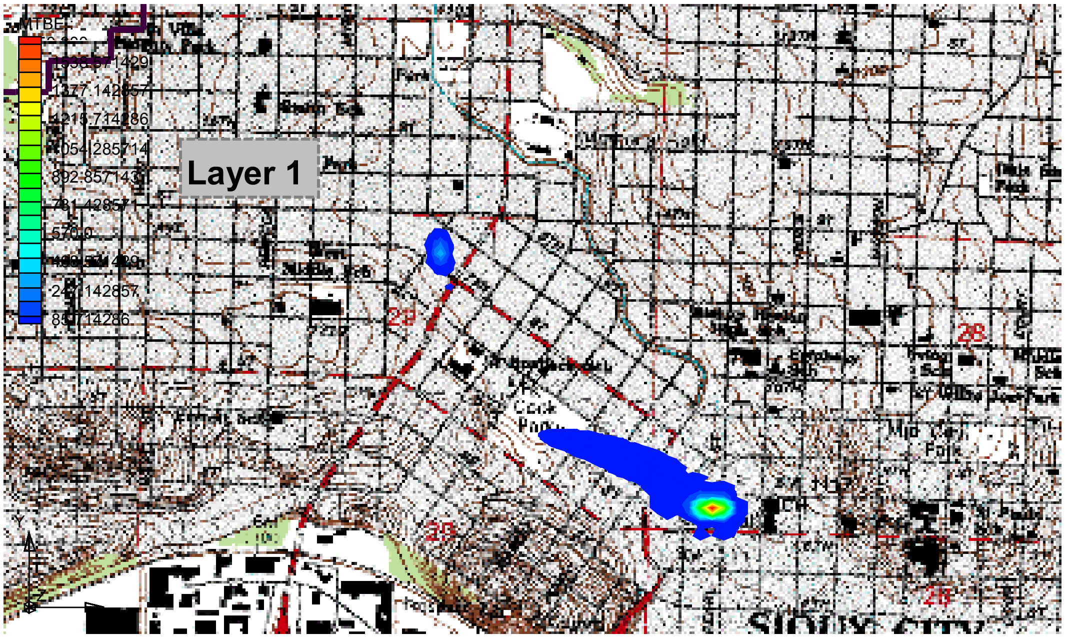


Figure C-9 Benzene concentrations at 10 years in layer 1 (top) and in layer 2 (bottom) at Cook Park



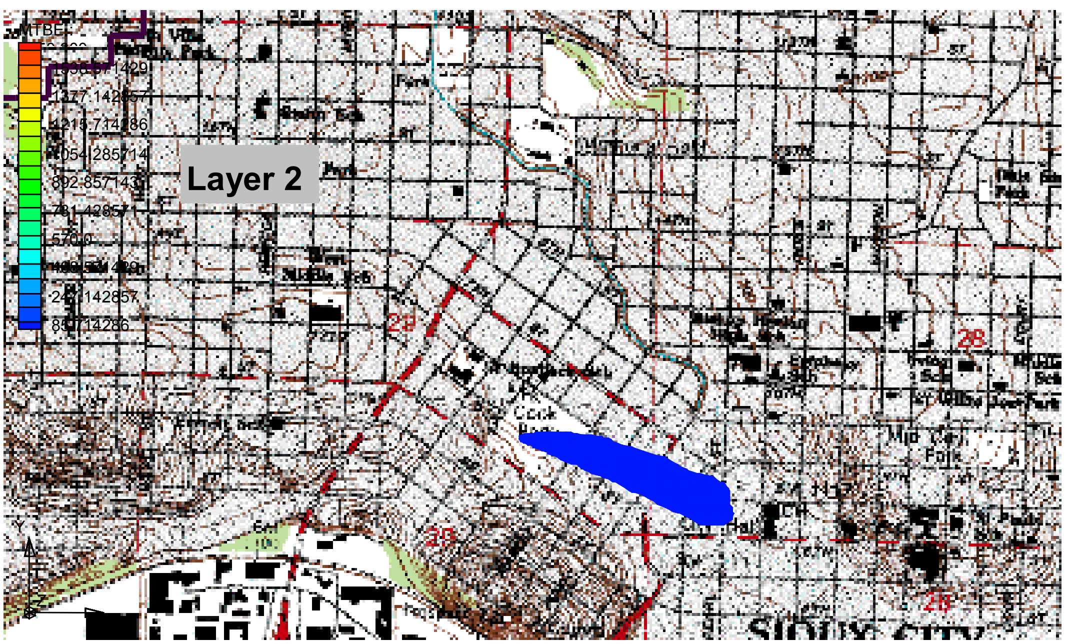


Figure C-10a MTBE concentrations at 10 years in layer 1 (top) and in layer 2 (bottom) at Cook Park

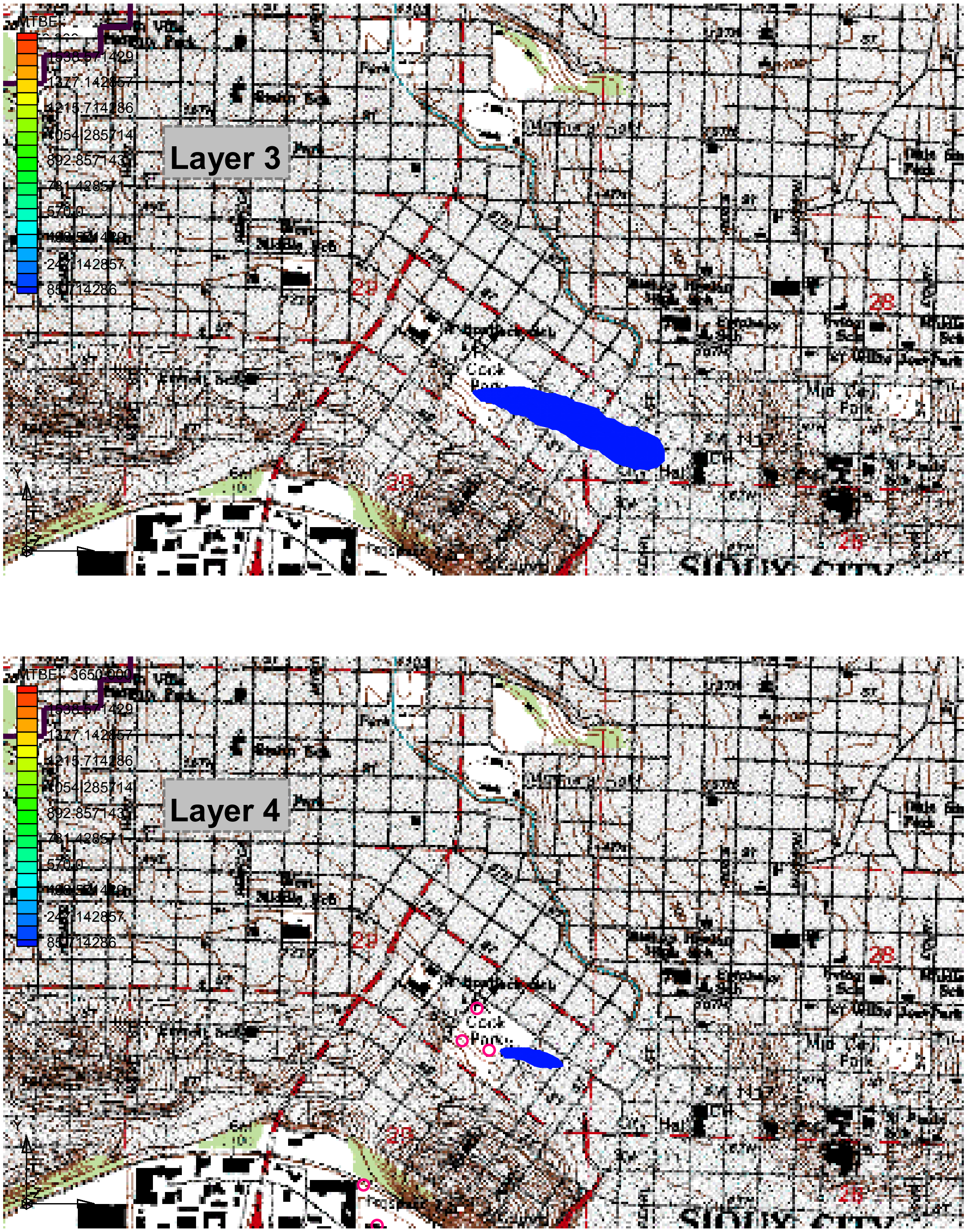


Figure C-10b MTBE concentrations at 10 years in layer 3 (top) and in layer 4 (bottom) at Cook Park

VI. FINAL THOUGHTS

The three examples are offered as illustrations of approaches one might take when developing numerical groundwater models to aid understanding of the existing situation and possible corrective actions at a LUST site. It must be stressed that before any modeling begins, all concerned parties must have a clear idea of the problem at hand, and the questions a numerical model can and cannot address.

In all three examples the scale of the problem far exceeded the dimensions and cleanup requirements of merely one high-risk LUST site. The labor-intensive modeling effort was justified in each example by the looming expense of remediating contaminated water supplies for the communities involved, and protecting those supplies from future contamination. The two of us spent time researching and building each model in proportion to the complexity of the model. Total time invested in the Climbing Hill model was about four person-days; in the Cook Park model, it was about twenty person-days; the Ida Grove model required an intermediate amount of time. Preparation of the write-ups given above for each model added another three to six person-days to the effort for each. Furthermore, these models were built lacking important, site-specific information that would come with the costs of additional assessment work in a Tier 3 effort and additional sampling and modeling needed to calibrate the transport models. Thus, a groundwater professional must carefully consider the economic factor before proposing a Tier 3 numerical modeling effort. In cases where a public water supply is affected, the effort is easily justified. In simpler cases, for example where a plastic water line is in a simulated plume from one LUST source, the economic considerations might mitigate toward corrective actions not involving numerical modeling.

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